

重要太阳爆发活动事件

科技基础性工作专项《我国太阳物理历史观测资料整编》

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重要太阳爆发活动事件

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前 言

“太阳活动对地球环境和灾害的影响及其预报”是《国家中长期科学和技术发展规划纲要(2006-2020 年)》前沿科学问题中的主要研究方向之一，当前工作是科技基础性工作专项项目“我国太阳物理历史观测资料整编”（项目负责人：林钢华，项目编号：2014FY120300）第四课题“太阳活动预报资料的整编”（课题负责人：杜占乐）研究内容之一。

对日地空间卫星设备、宇航员安全、近地空间地磁层、电离层及通讯设备造成重大影响及危害的太阳活动事件往往是那些指向地球的比较强、也比较强的太阳爆发活动事件，对这些比较强的太阳爆发活动事件进行研究、预报，进而采取必要的安全防护措施是太阳物理及空间物理重要研究课题之一，问题在于对这些大而强的太阳爆发活动事件进行准确预报、分析太阳上何时、何地产生多大规模、多大强度的太阳爆发活动、它们什么时候、是否到达地球、是否对近地空间环境造成重大危害也是比较困难的工作，但这对于保障空间站、卫星的安全运行、宇航员的身体健康、通讯设备的安全来说是必须要做的工作。

我们整理了历史上影响比较大的八个重要太阳爆发活动事件的相关资料，期望能为我国太阳物理和空间天气研究与应用提供重要太阳爆发活动事件的综合数据、研究文献等资料。本工作由太阳活动预报研究单元全体成员参与完成。

我们对这些事件的观测特征进行综合概述，如太阳耀斑强度、CME（日冕物质抛射）传播、高能粒子事件及对地效应，收集了与事件相关的研究文献，重点对引用比较多的研究论文进行了综合整理，案例分析重点放在哪些作者用什么数据、什么方法得到了什么结果（论），配以重要的分析图片及相关影像资料，整理该事件的主要科学贡献，如对物理现象及参量的研究、运动与机制研究、CME特性及其传播、对地效应等，以及主要参考文献、观测仪器（数据）等。

期望读者能从中了解太阳爆发活动的现象及对地影响，能快速、便捷地了解重要太阳爆发活动的观测现象、事件强度、运动机制、对地影响以及相关观测数

据、研究文献、研究水平及研究动态。期望读者能从中找到自己感兴趣的相关太阳爆发活动现象进行深入研究，找出这些现象的普遍规律与特殊性，提高太阳爆发活动的预报能力正是编纂本资料的初衷。

最后，由于作者的知识范围有限，加之时间限制，并且重点放在了对这些事件的太阳物理方面的资料整理上，因此，对这些事件的综述难免会有所遗漏，希望对这方面感兴趣的专家、学者、工作人员纠正其中的不足，提供相关的研究内容、研究方法、研究成果等，以便将来进一步提升本工作研究范围的全面性、实用性。

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第一章 巴士底事件（NOAA9077 活动区）

1.1. 事件概述

NOAA 9077 活动区于 2000 年 7 月 8 日从太阳东边缘出现,7 月 22 日从太阳西边缘消失。2000 年 7 月 14 日该活动区产生了多个太阳 X 射线耀斑,其中最大的达到 X5.7 级(见图 1.1),伴随全晕 CME 事件,造成超强高能质子事件,引起电离层扰动、S3 级辐射风暴, G5 等级超级地磁暴 ($Dst = -300nT$)。这次空间天气事件由于发生在巴士底日,故称为“巴士底事件”(“Bastille Day Event”)。

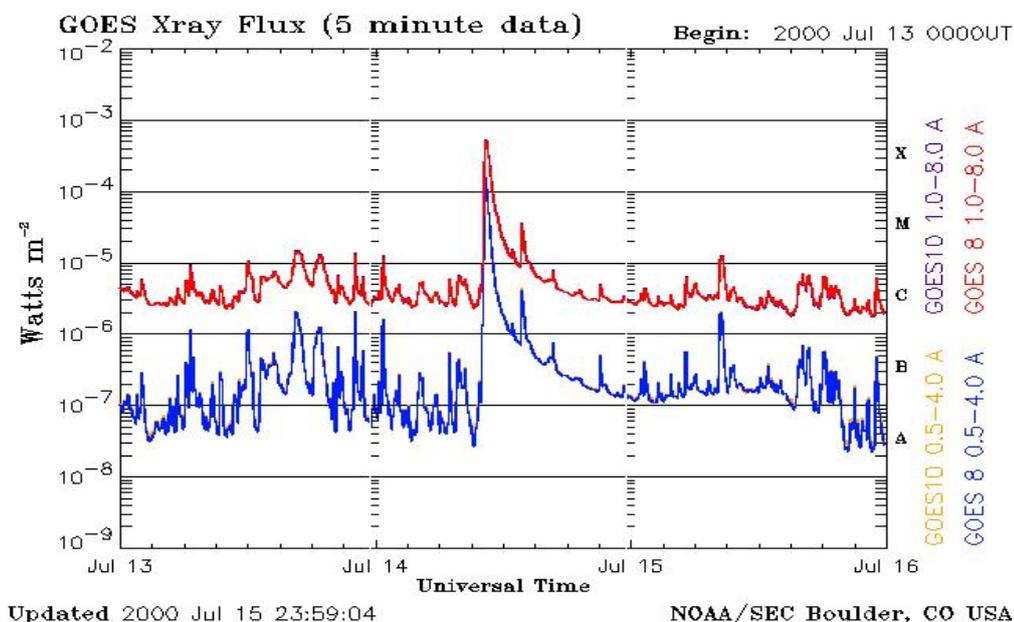


图 1.1: GOES 卫星软 X 射线流量 (2000-07-14 1003 1024 1043 X5.7 7.50E-01 9077)

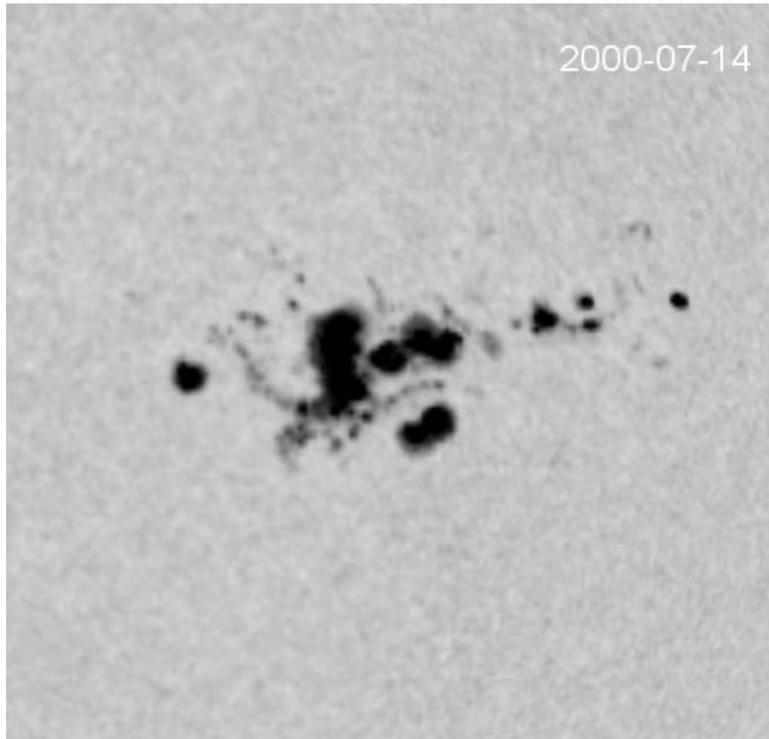


图 1.2: 2000 年 7 月 14 日黑子图 (SOHO/MDI)

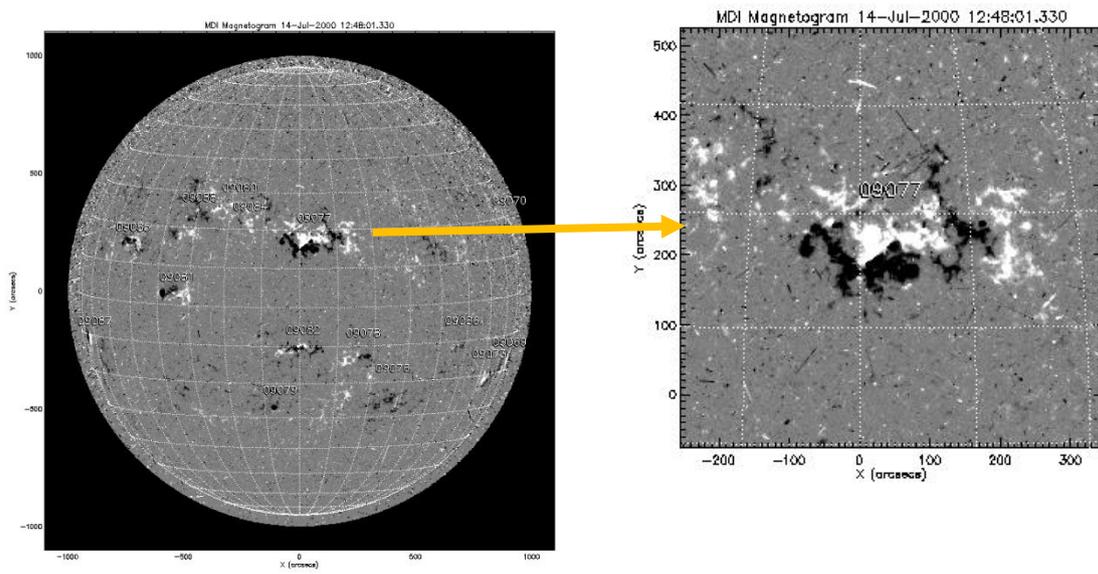


图 1.3: MDI 磁图: NOAA 9077 活动区在 2000-07-14 出现在日面中心

表 1. 1: NOAA 9077 耀斑参数 (Smith 等, 2001, Solar Physics, 204, 229 - 254)

TABLE IV
Flare times^{a,b}

Day	Hr:min (UT)	H α location	H α imp.	X-ray class
190	07:32	N17 W07	1N	
190	13:21	N17 W08	1F	C3.1
191	07:18	N16 E72	1N	M5.7
191	08:22	N19 W17	1F	
192	13:55	N18 E52	1N	M1.4
192	18:32	S18 W32	1N	M1.8
192	21:32	N18 E49	2B	M5.7
193	13:20	N18 E27	2N	
193	18:49	N16 W56	1N	M1.1
194	04:54	N16 E31	1N	M1.2
194	10:15	N17 E27	2B	X1.9
194	18:48	N16 W64	2F	M5.7
194	20:13	N17 W65	SF ^c	
195	16:05	N13 E65	1N	M1.1
195	16:16	N19 W75	1F	M1.5
195	17:52	N19 W82	1N	
195	18:46	N18 E08	1F	M1.2
196	08:09	N14 E53	1F	
196	10:21	N22 W07	3B	X5.7
196	10:53	N17 E01	2B	
196	13:46	N20 W08	1N	M3.7
197	05:55	S09 W13	1F	
198	01:22	S11 E53	1N	C6.3
198	02:05	N09 E81	1N	
198	19:36	S13 E48	1N	C6.5
198	20:46	S04 E68	1N	C4.9
198	21:49	N14 E76	1N	M1.1
198	23:41	N17 W38	2F	M1.4
199	08:30	S10 E36	1F	C5.3
199	13:37	S08 E31	1F	M1.2
199	18:06	N19 W47	1F	
199	20:16	S11 E36	1N	M2.4
199	22:31	S12 E30	1F	

^aObtained from Solar-Geophysical Data.

^bOnly H α flares with importance above subflare.

^cOne subflare included for electron timing.

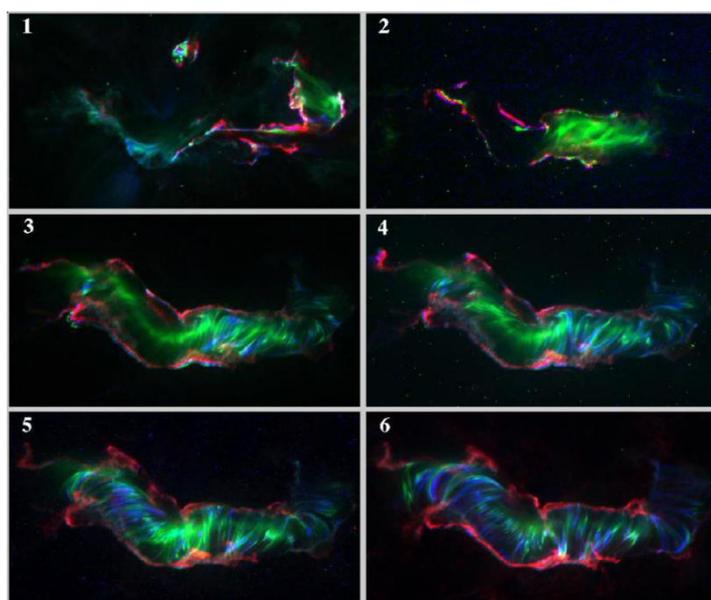


图 1. 4: TRACE 卫星 2000 年 7 月 14 日极紫外成像(蓝色:171 埃; 绿色:195 埃)

1.1.1. 事件特征

- 事件观测时间：NOAA 9077 活动区于 2000 年 7 月 8 日从太阳东边缘出现（N18E72），7 月 14 到达日面中心，7 月 22 日从太阳西边缘消失。
- 最大面积：1010 日面单位（1 日面单位=太阳半球面 $\times 10^{-6}$ ）；时间：2000 年 7 月 12 日；位置：N18E33。
- 磁位型： $\beta\gamma\delta$
- X 级耀斑数量：3
- M 级耀斑数量：12
- 最大耀斑级别：X5.7 级；时间：2000-07-14 10:24 UT；位置：N17 E01。
- 高能事件：超强高能质子事件。
- CME 事件：全晕 CME。
- 对地效应：电离层扰动、S3 级辐射风暴，G5 等级超级地磁暴（Dst = -300nT, 7 月 16 日），Kp=8。

1.1.2. 观测特征

在 NOAA9077 活动区期间产生了一个 X5.7 级别的耀斑，15 分钟之后，高能质子轰击到地球，引发了 S3 级辐射风暴，这是 1989 年以来比较大的太阳辐射事件。这次质子事件比之前 1995 的 SOHO 和 1997 年的 ACE 记录到的任一事件都要强 4 倍以上，伴随着耀斑之后是整个日冕的日冕物质抛射和在 7 月 15-16 日的大地磁暴（Dst = -300nT）。在 7 月 15 日之后几小时的峰值达到极端强烈的 G5 等级，造成 3 颗 GOES 同步卫星在相对长时间进入磁鞘。

表 1. 2: NOAA 9077 活动区的 3 次 X 级耀斑

序号	日期	起始时刻	峰值时刻	结束时刻	位置	耀斑级别	峰值流量
A	2000-07-11	1212	1310	1335		X1	3.10E-01
B	2000-07-12	1018	1037	1046	N17 E27	X1.9	1.40E-01
C	2000-07-14	1003	1024	1043	N17 E01	X5.7	7.50E-01

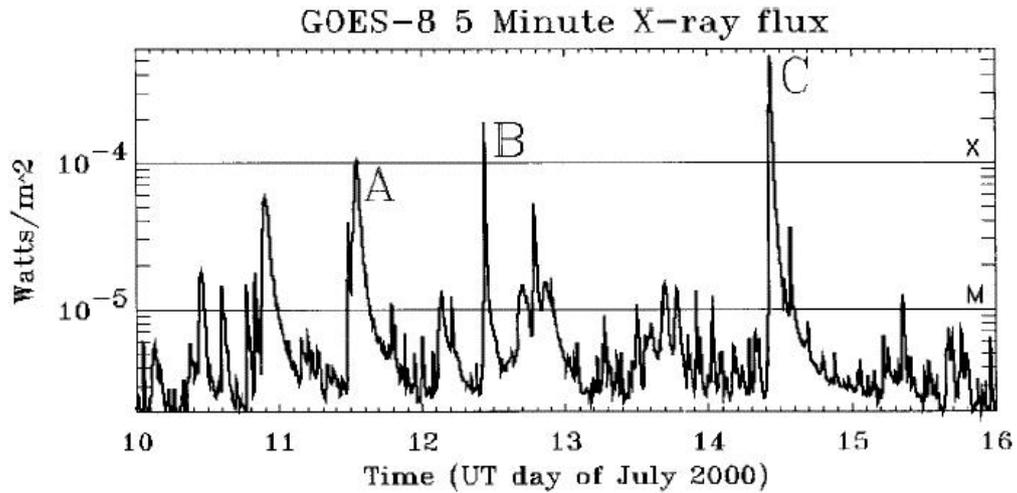


图 1. 5: GOES 卫星软 X 射线流量耀斑观测(Andrews, 2001, Solar Physics, 204, 181-198)

1.2. 相关事件案例研究

2000 年 7 月 14 日 NOAA 9077 活动区产生的 X5.7 耀斑到目前为止虽然不是最强的，但伴随指向地球的全晕 CME，在 7 月 15-16 日产生了大地磁暴（Dst = -300nT），高能质子轰击到地球，引发了 S3 级辐射风暴。因此，与该事件相关的研究范围包括从日面光球层、过渡区、日冕层、行星际空间到近地空间的地磁层、电离层、热层等各个领域。与该事件有关的研究论文不少于 150 篇，我们从中选择了部分文献，特别是太阳物理方面的，加以综述。

1.2.1. 多波段综合分析

Aschwanden 和 Alexander（2001, Solar Physics, 204, 93 - 121）利用 Yohkoh/HXT、Yohkoh/SXT、TRACE 和 GOES 卫星上不同波段的光变曲线数据来综合研究 9077 活动区，并分析了耀斑等离子体的冷却过程。

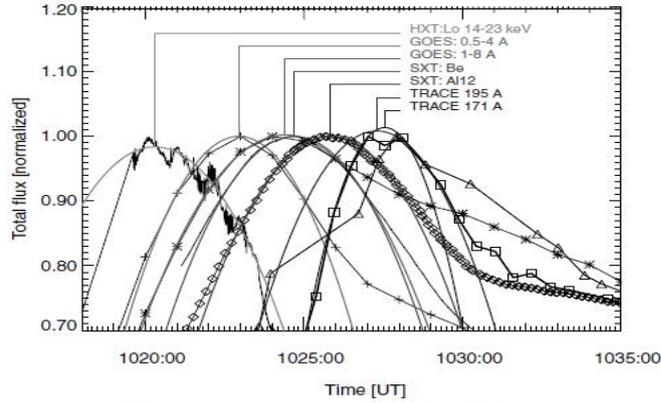


Figure 9. Top: coregistered light curves from *Yohkoh*/HXT, *Yohkoh*/SXT, GOES, and TRACE, normalized to unity. Bottom: enlarged portion of the flare peak times, fitted by parabolic curves to determine the mean peak times for each wavelength. Only datapoints in the top 20% of the peak fluxes are considered for the parabolic fits. One single low point of the TRACE 195 datapoints (triangles) before the peak is discarded because of saturation effects. The relative time delays of the peaks are listed in Table I.

图 1. 6: 不同仪器观测到的 NOAA9077 光变曲线

表 1. 3: 不同仪器测量的峰值时间差别

TABLE I
Peak times of total flux in different instruments and wavelengths, and time delays relative to hard X-ray HXT/LO peak.

Instrument wavelength	Peak time ($t_{\text{peak}}[MK]$)	Time delay (t_{delay})
HXT Lo 14–23 keV	10:20:18 UT	0 s
GOES 0.5–4 A	10:22:57 UT	159 s
GOES 1.0–8 A	10:24:24 UT	246 s
SXT Be	10:24:42 UT	264 s
SXT Al12	10:25:50 UT	332 s
TRACE 195 A	10:27:18 UT	420 s
TRACE 171 A	10:27:33 UT	435 s

1.2.2. 磁对消与暗条爆发

张军等(2001, ApJL, 548, L99-L102)利用 HSOS, TRACE, EIT 和 LASCO 数据, 分析了 NOAA 9077 事件在源活动区的磁场演化, 发现事件过程中唯一明显的磁场变化是在暗条附近多处磁对消。此外, 暗条的所有初始扰动及暗条周围的初始变亮都发生在对消点。他们认为, 低层大气中慢磁重联(以通量对消观测形式)在导致大磁活动的全局不稳定性方面起了支配作用。

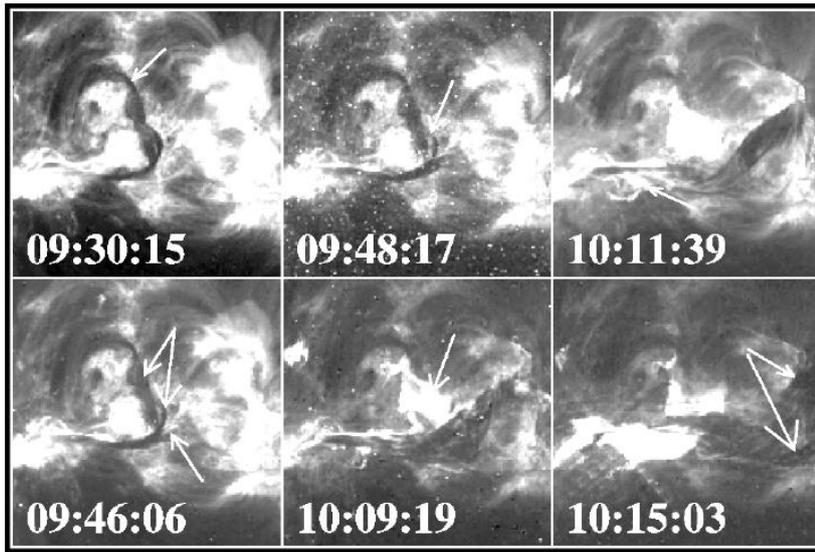


FIG. 2.—Time sequence of *TRACE* 195 Å images showing the evolution of the filament. The field of view is about $290'' \times 290''$. The arrows in this figure are described in the text.

图 1.7: 暗条爆发顺序 (TRACE 1600 Å)

表 1.4: 不同波段事件的爆发事件顺序

TABLE 1
TIME SEQUENCE OF THE SOLAR EVENT

Time (UT)	Phenomena
04:09	H α brightenings on both sides of filament (from HSOS)
08:22	Brightening of filament at region shown by window in Fig. 1 in <i>TRACE</i> 1600 Å images
09:46	Bifurcating of filament in the inflection point in <i>TRACE</i> 195 Å images
09:48	Breaking of the thinner filament thread in 195 Å images
10:00	Breaking of the filament seen in EIT images
10:03	Appearance of the X5.7 flare in H α images
10:09	Appearance of flare patch at the broken point at EUV
10:24	Maximum phase of the X5.7 flare (from EIT)
10:54	First appearance of the halo CME in C2 field
11:18	First appearance of the halo CME in C3 field

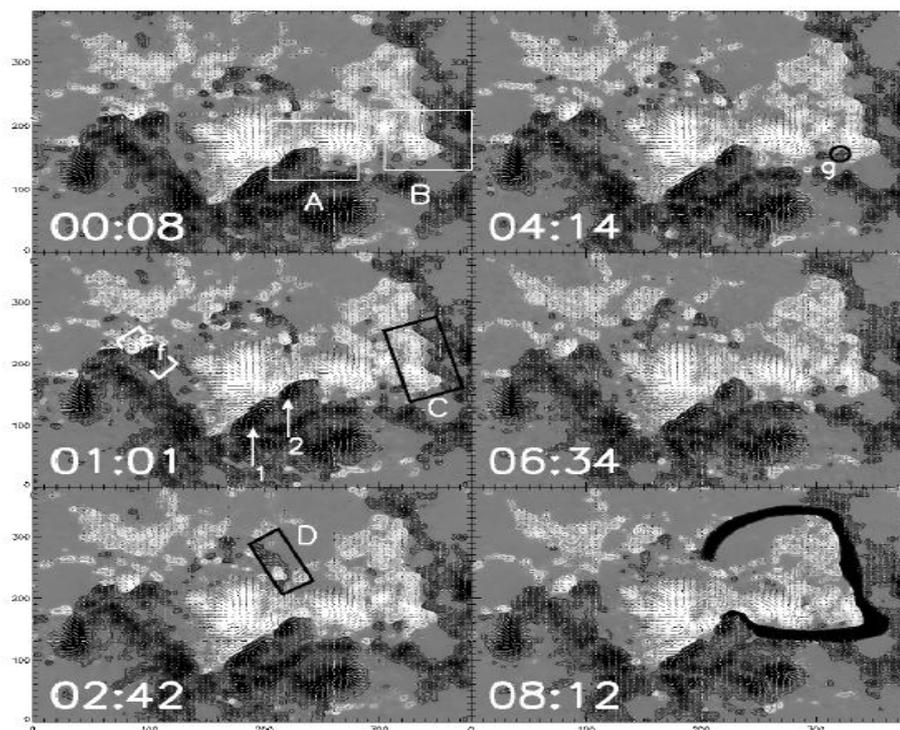


FIG. 3.—Time sequences of vector magnetograms observed at HSOS. The line-of-sight component of the magnetic field is presented by gray-scale patches and isogauss contours with levels of ± 100 , 200, 400, and 800 G. White patches represent positive polarity fields, and black patches represent negative fields. The transverse component is shown with short lines, with lengths proportional to the relative field strength. The dark ribbon at 08:12 UT is the H α filament at 08:42 UT. The windows and letters in this figure are described in the text. On the x-axis, 1 unit = $0''.613$; on the y-axis, 1 unit = $0''.425$.

图 1.8: 怀柔矢量磁场测量的暗条时间演化顺序

1.2.3. 高能粒子的重离子能谱由激波加速引起

Tylka 等(2001, APJL, 558, L59 - L63)利用搭载在 Wind 上的设备 Energetic Particle Acceleration, Composition, and Transport (EPACT) 中的 Low-Energy Matrix Telescope (LEMT)数据, 搭载在 Advanced Composition Explorer (ACE)上的仪器 Solar Isotope Spectrometer (SIS) 和 Electron, Proton, and Alpha Monitor (EPAM) 数据, 研究了“巴士底”事件期间高能粒子的重离子 (Fe) 能谱的特殊性, 铁能谱近似幂律分布, 而其他则为指数分布, 认为 NOAA9077 活动区是由双源激波加速引起的。

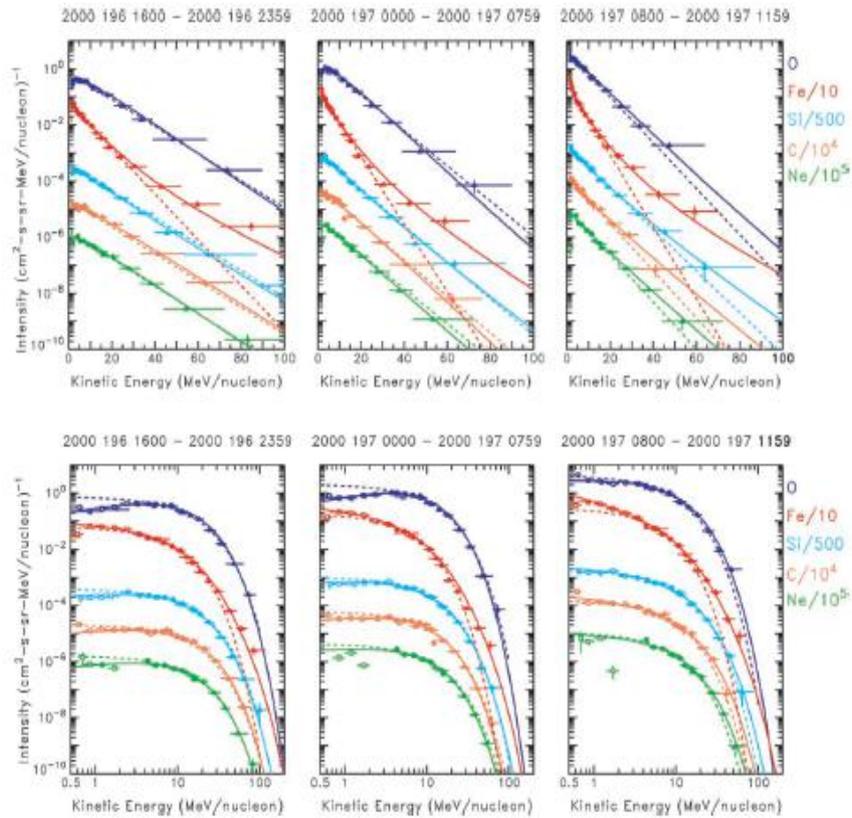


FIG. 1.—Heavy-ion energy spectra in the 2000 July 14 solar particle event. Times are noted at the top. The associated X5.7 flare occurred at ~10 UT on day 196, and the associated shock arrived at 1 AU at ~1430 UT on day 197. Species are color-coded and appear in the same order as in the legends at the right. Note the scale factors. Data are from *Wind*/EPACT/LEMT (*filled circles*), *ACE*/EPAM (*open squares*), and *ACE*/SIS (*filled triangles*). Dashed lines are exponential fits to LEMT data only (Reames et al. 2001). Solid curves are model fits, as described in the text.

图 1.9：“巴士底”事件期间重离子能谱的变化

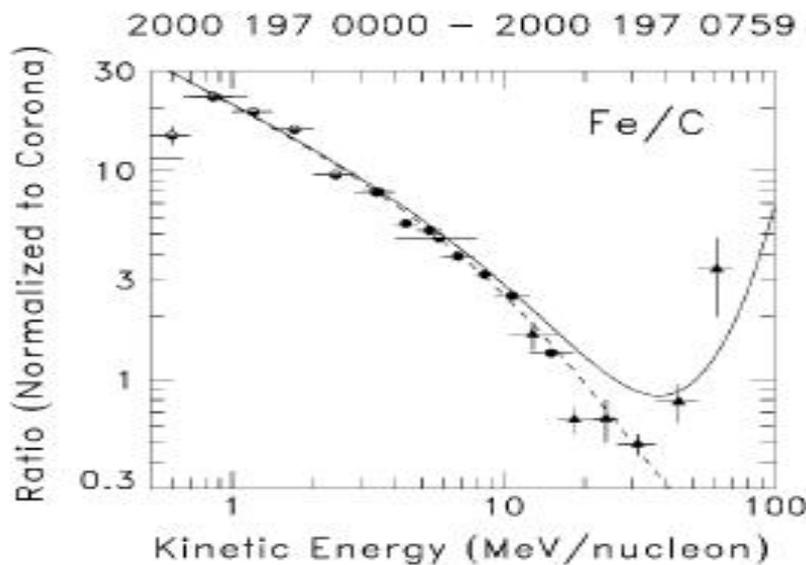


FIG. 4.—Fe/C as a function of energy, normalized to the mean coronal value of 0.288 (Reames 1995). The dashed curve uses solar wind component Fe only, and the solid curve includes solar wind plus remnant flare suprathermals.

图 1.10：铁/碳比作为能量的函数

1.2.4. 黑子演化研究

Liu 和 Zhang (2001, A&A, 372, 1019-1029) 利用怀柔太阳观测站 (HSOS) 的 Hbeta 谱线及光球矢量磁场(SMFT)数据, TRACE 的白光像 (WL, 5000Å), 以及 SOHO 上的全日面磁图 (MDI) 数据, 基于自行运动分析了 7 月 14 日“巴士底”耀斑事件期间黑子的大规模运动与大耀斑的关系, 发现 (1) 特殊的磁场形态和快速连续的碎裂导致活动区始终处于高剪切状态; (2) 一个黑子群的运动方向与暗条被切断并激活的位置之间存在良好的空间对应关系; (3) 快速浮现磁通量系统的运动特征显示黑子运动和最大耀斑之间有良好的相关性, 表明在 7 月 14 日双带耀斑初始是由通量系统的连续浮现促成的, 认为大耀斑总是与新浮现的强磁通量系统相连。

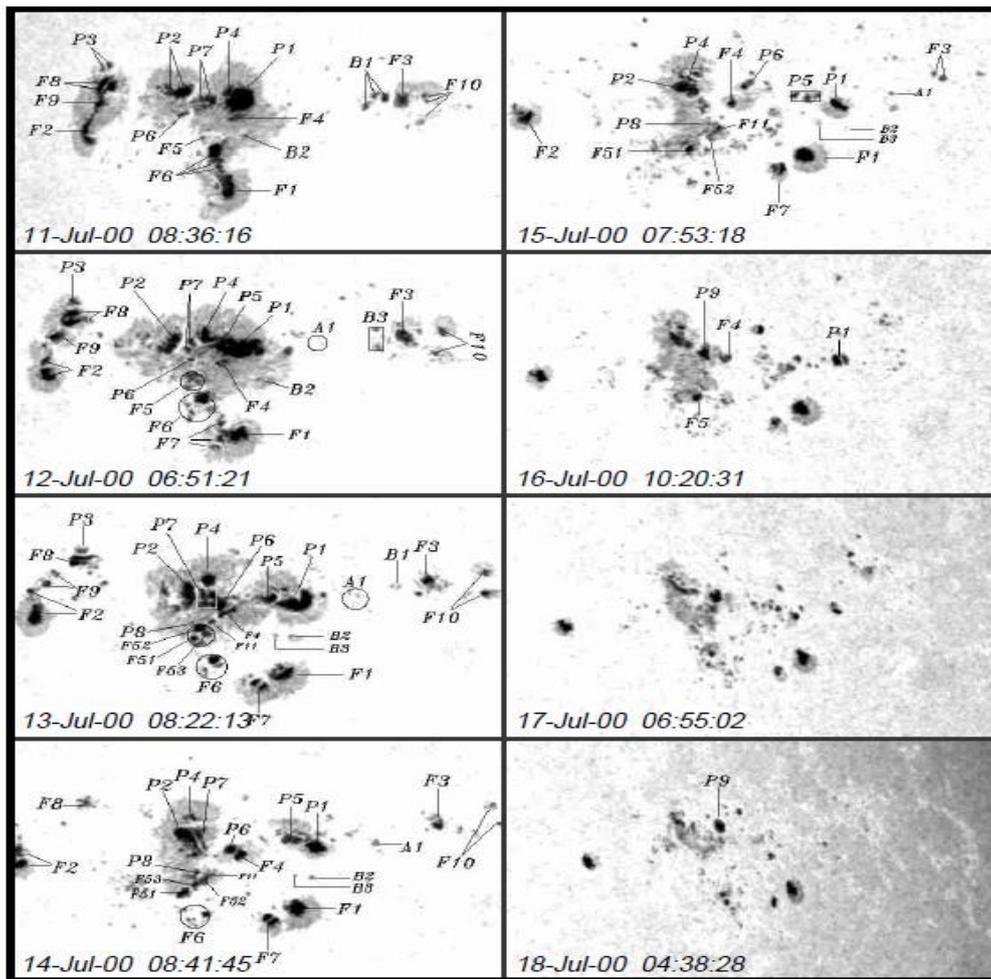


Fig. 1. A time sequence of white-light observations of AR 9077 from TRACE. The size of images is $6' \times 4'$. The preceding (positive) spots are marked with "P" and "A", following (negative) are marked with "F" and "B". North is up and east is to the left.

图 1. 11: TRACE 的白光像观测到的 9077 活动区事件演化

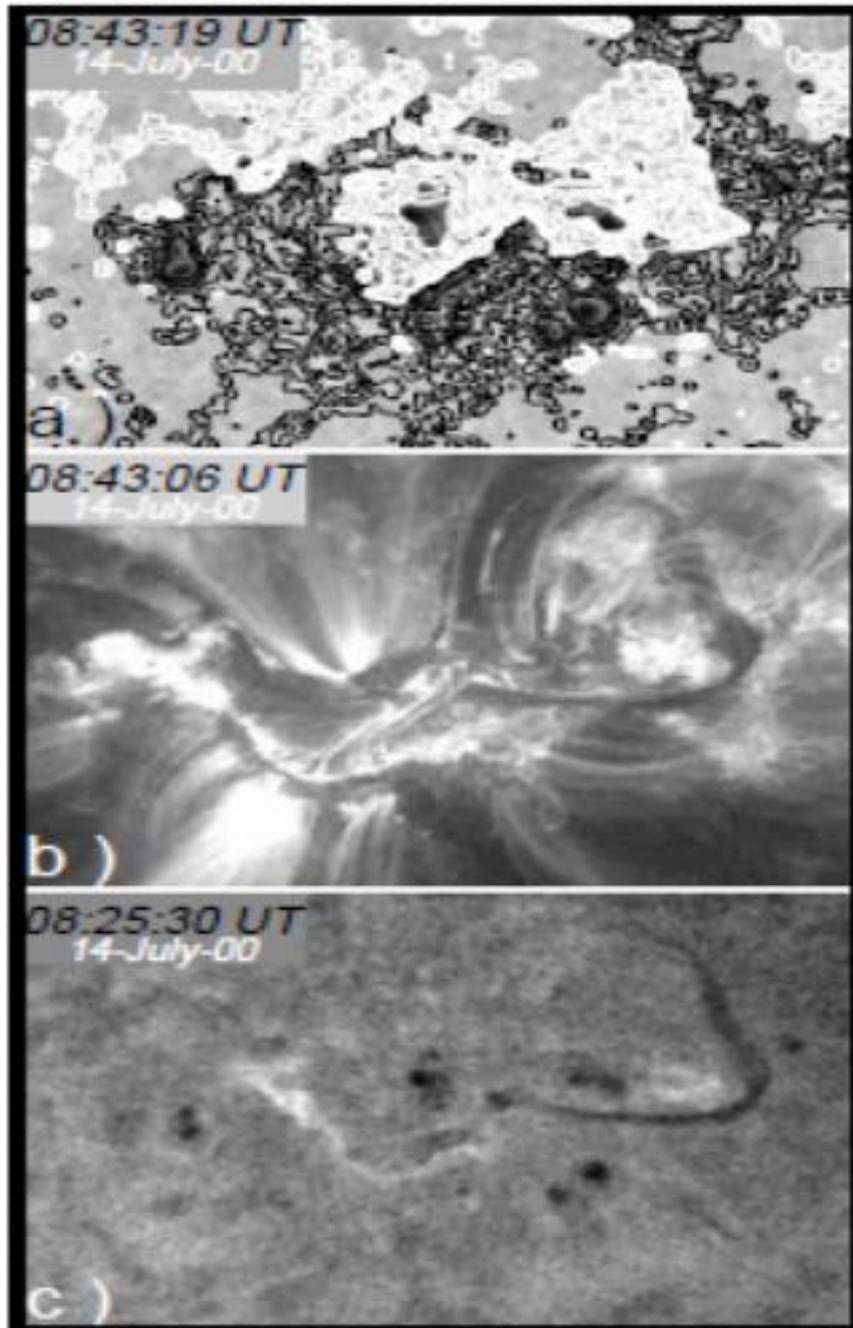


Fig. 2. Global morphology of the AR 9077 on July 14, 2000. a) A white-light image overlaid by the longitudinal photospheric magnetic field of HSOS, showing the polarity of every spot clearly. White contours represent positive polarity, black represent negative; b) A TRACE 171 Å image of the region at the same time, notice a twisted filament formed along the right PIL; c) An H β image taken from HSOS. The POV is 4.9' \times 3.3'.

图 1.12: 黑子群演化

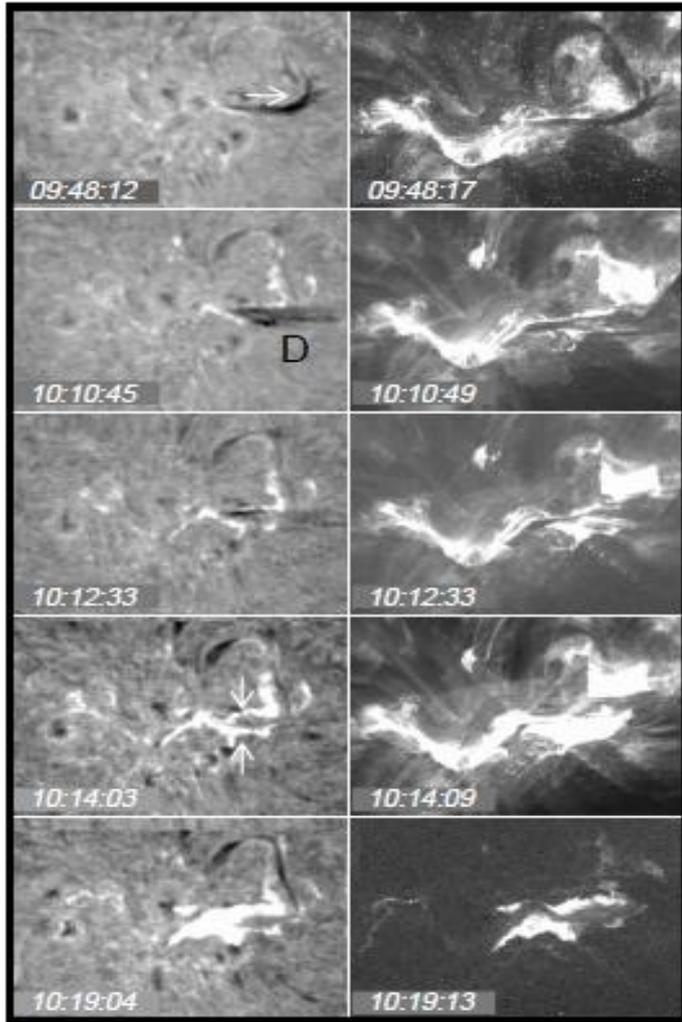


Fig. 6. A series of H β (left column) and TRACE images (right column, with 195 Å at 10:12:33, others are in 171 Å), obtained almost at the same time, which show the quick changes near the point "D" before and during the major flare took place on July 14. The horizontal arrow indicates the activation near the inflection point of the filament, and the two vertical arrows indicate the two ribbons of the major flare. The FOV is $5.2' \times 3.6'$.

图 1.13: Hbeta(左) 与 TRACE171/195Å(的演化)

1.2.5. 2000 年 7 月 14 日太阳耀斑中的磁绳结构及相关高能过程

颜毅华等 (2001, APJL, 551, L115 - L119)通过对 2000 年 7 月 14 日 NOAA 9077 活动区 X5.7/3B (10:24 UT)耀斑前的三维磁场非线性无力场外推,发现了磁绳存在,磁绳位于暗条中性线上方,磁绳的磁力线绕绳转动超过 3 圈,具有不同方向的多层磁拱覆盖其上,拱与 TRACE 观测一致,这种磁场结构对于解释 Ha、EUV 及射电观测到的高能耀斑过程提供了一个有利的模型。EUV 1600 Å观测到的磁绳位置的间歇性增亮导致耀斑爆发,意味着磁绳的不稳定性可能触发了耀斑事件,分米波漂移的脉冲结构被认为是反映了 CME 的初发阶段。

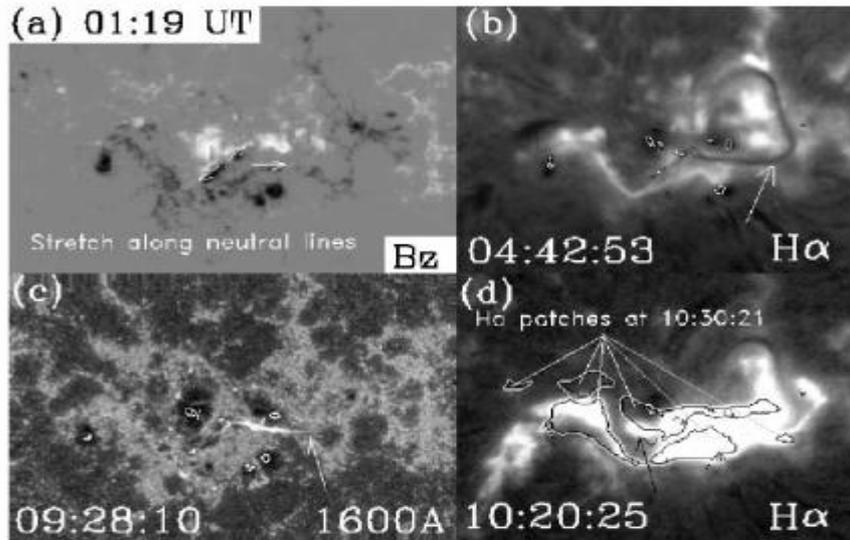


FIG. 1.—(a) Huairou mosaic longitudinal magnetogram with white (black) indicating north (south) polarity of more than 3000 G. (b) Huairou $H\alpha$ image showing a long triangle-shaped filament. (c) *TRACE* EUV 1600 Å image showing a bright lane in a space above the filament. (d) Huairou $H\alpha$ flare image at 10:20:25 UT, overlaid with flare ribbon patches at 10:30:21 UT. The small contours overlaid on the EUV and $H\alpha$ images indicate the locations of sunspots. Each panel is about $6' \times 4'$ in size; north is to the top, and west is to the right.

图 1. 14: (a)怀柔纵向磁图, (b)怀柔 $H\alpha$ 图, (c) TRACE EUV 1600 Å图, (d)怀柔 $H\alpha$ 耀斑图

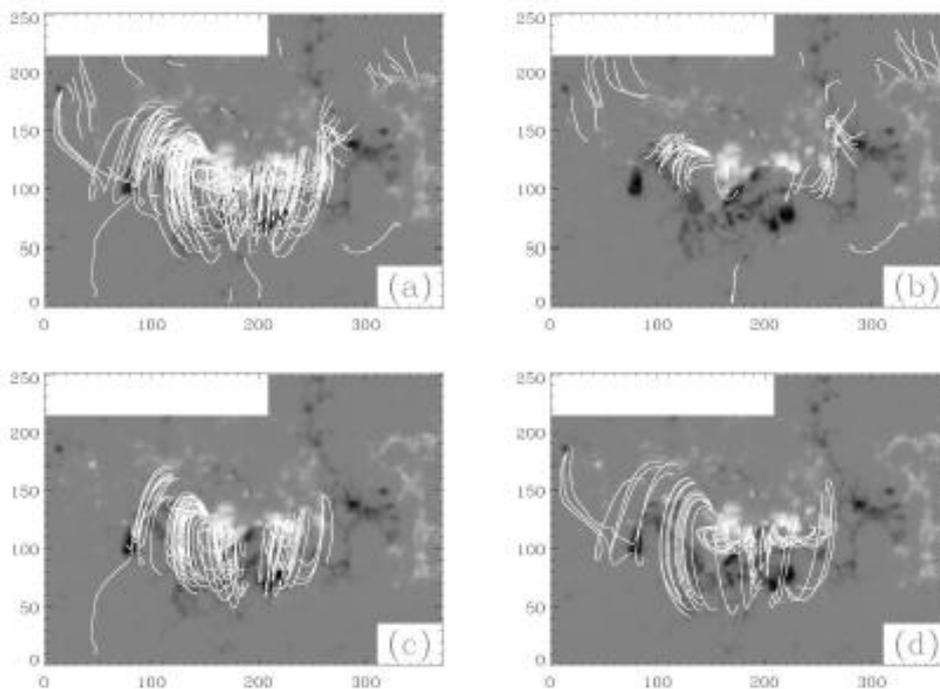


FIG. 3.—Reconstructed magnetic field lines projected onto the photospheric magnetogram of Fig. 1a. (a) Overall calculated field lines that are closed to the photosphere; (b) lower lying lines ($2'-25'$ high) showing arcades across the neutral lines; (c) higher lying lines ($25'-30'$ high) showing arcades with different orientations; and (d) the magnetic rope along the neutral line embraced by overlying arcades. The blank areas are due to the mosaic of the vector magnetograms.

图 1. 15: 重建的磁力线

1.2.6. 三维磁重联研究

Somov 等(2002, APJ, 579, 863 - 873)利用 Yohkoh 硬 X 射线、SOHO (MDI) 和怀柔磁场数据, 认为“巴士底”耀斑是由日冕分割线处的三维磁重联引起, 磁分割面的运动由两种运动导致。一种是平行于光球中性线的剪切流动, 增加日冕中磁力线长度, 并产生额外磁能。另一个是指向中性线的汇聚流动, 耀斑前产生电流层, 并提供足以产生大耀斑的额外能量。

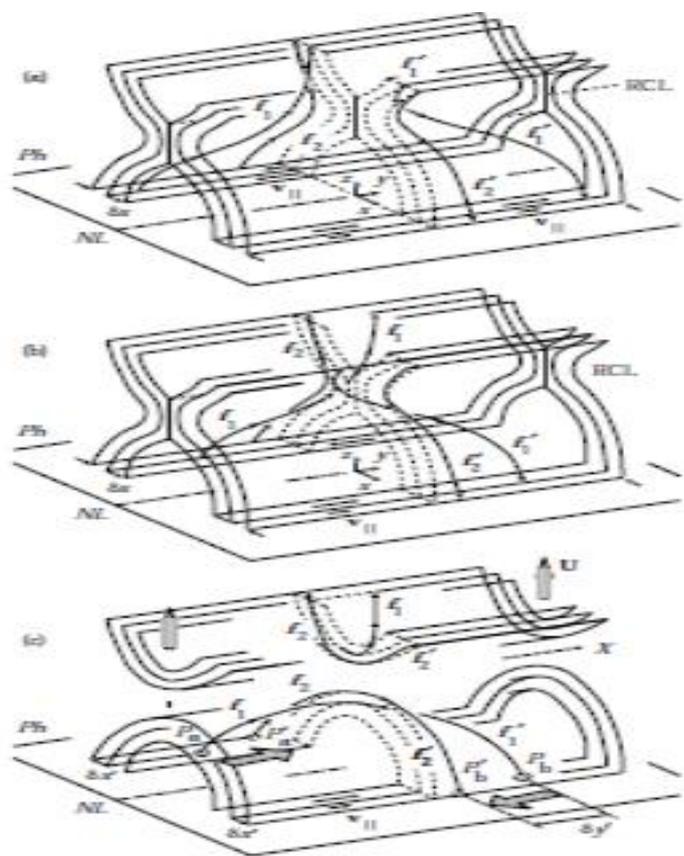


FIG. 6.—(a) Converging flow across the RCL. This shear flow in the photosphere makes the field lines longer. (b) A preflare state of the magnetic field in an AR. (c) Rapidly decreasing footpoint separation during a flare.

图 1.16: 三维磁重联模型

1.2.7. 活动区非势性演化分析

Deng 等 (2001, *Solar Physics*, 204, 13 - 28) 利用怀柔观测站的矢量磁场成像数据, 研究了“巴士底”耀斑事件的非势演化, 认为 (1) 剪切角在暗条通道发生了巨大的变化, 在暗条的关键地点, 磁剪切从正转变为负; (2) 大耀斑事件前电流系统破坏, 并形成新的弱电流系统; (3) 耀斑前源场减弱, 光球层的自由磁能密度降低。这些现象发生在磁对消过程中大量磁通消失的地方, 这些磁场非势性的演化代表了磁能及复杂性从低层大气到日冕的转移。

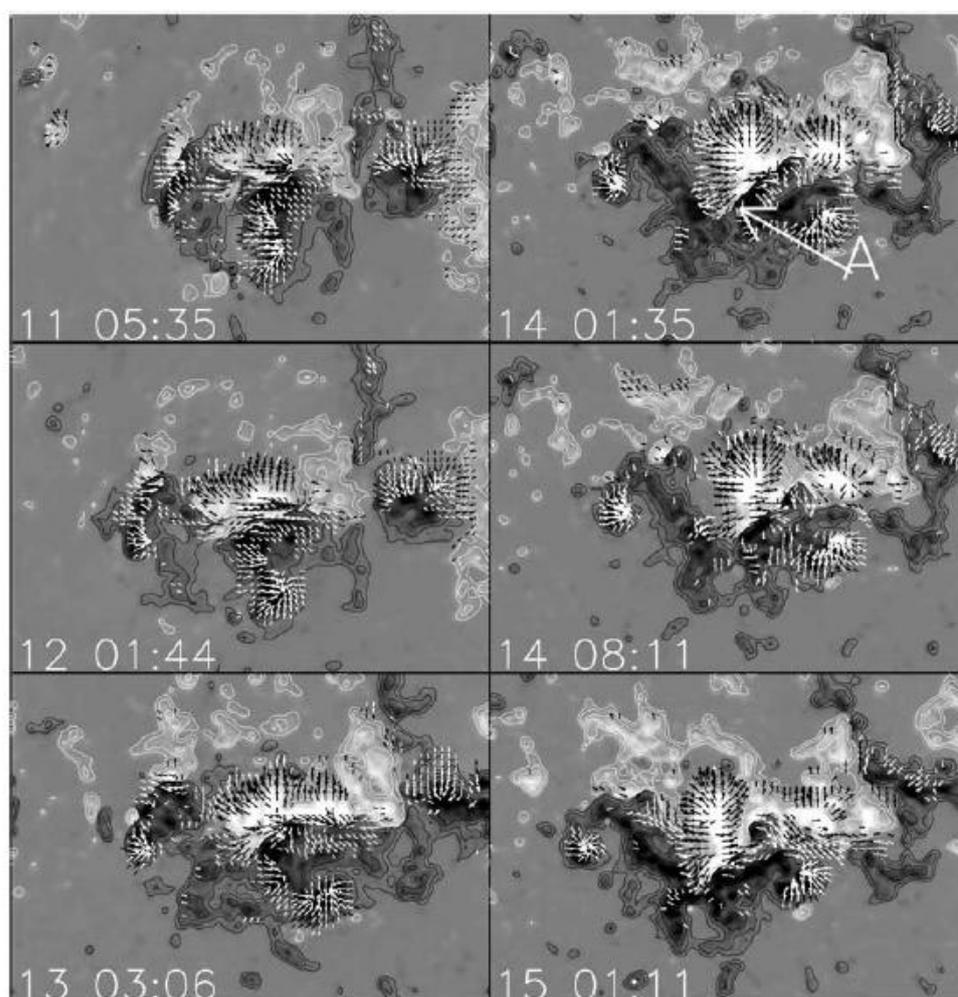


Figure 2. Daily evolution of the vector magnetic field in NOAA AR 9077 from 11 to 15 July. The line-of-sight magnetic component is presented by gray-scale patches and isogauss contours. Contour levels are ± 80 , 160, 320, and 640 G. Arrows denote the transverse magnetic component. 'A' is defined as in Figure 1.

图 1. 17: 7 月 11-15 日磁场演化

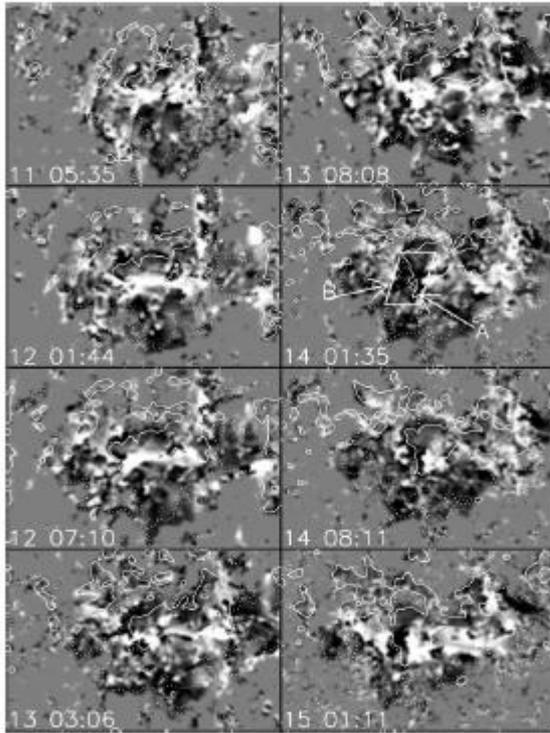


Figure 3. Daily evolution of magnetic shear angle from 11 to 15 July. The distribution of shear is scaled between $\pm 60^\circ$. The clockwise (counterclockwise) rotation from observed field to potential one is positive (negative), and white (black) in this figure. The longitudinal magnetic field is overlaid on the shear angle with contours. The solid contours denote positive field, and the dotted contours, negative field. Contour level is 80 G. At 01:35 UT, 14 July, we use a box ('B') to indicate a key site where magnetic shear angle underwent dramatic change. Arrow 'A' is defined in Figure 1.

图 1. 18: 7 月 11-15 日剪切角演化

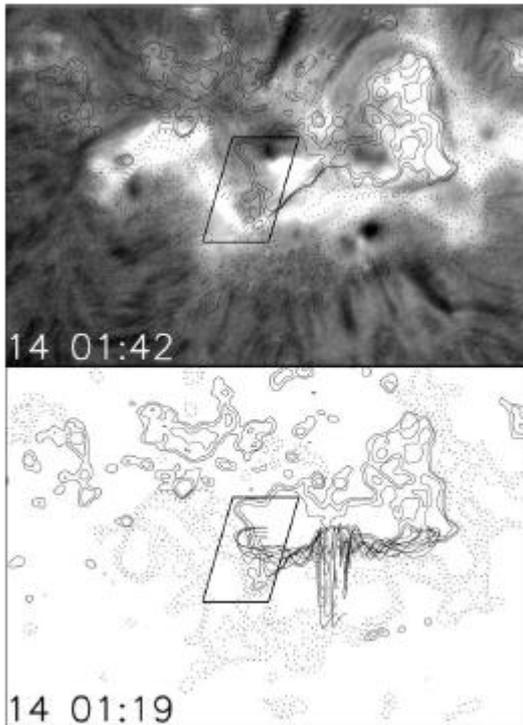


Figure 4. Magnetic ropes and filament channel. Upper panel: Ha image overlaid with longitudinal magnetic field, and the box is same as in Figure 3; lower panel: reconstructed magnetic rope overlaid with magnetogram. The solid (dotted) contours are positive (negative) field. Contour levels are: ± 80 G, 160 G, 320 G.

图 1. 19: 磁绳与暗条通道

1.2.8. “巴士底”大磁暴

Mitchell 等 (2001, GRL, 28, 1151-1154) 利用探测地磁层 IMAGE 中的 High Energy Neutral Atom imager (HENA) 比较了两个地磁暴, 一个“巴士底”大磁暴 (2000 年 7 月 15-16 日, $Dst = -300nT$), 另一个是小磁暴 (2000 年 7 月 10 日, $Dst = -55nT$), 小磁暴中引起 Dst 变化的离子基本是在开放飘移路径, 而大磁暴中引起 Dst 变化的离子主要是在封闭飘移路径。

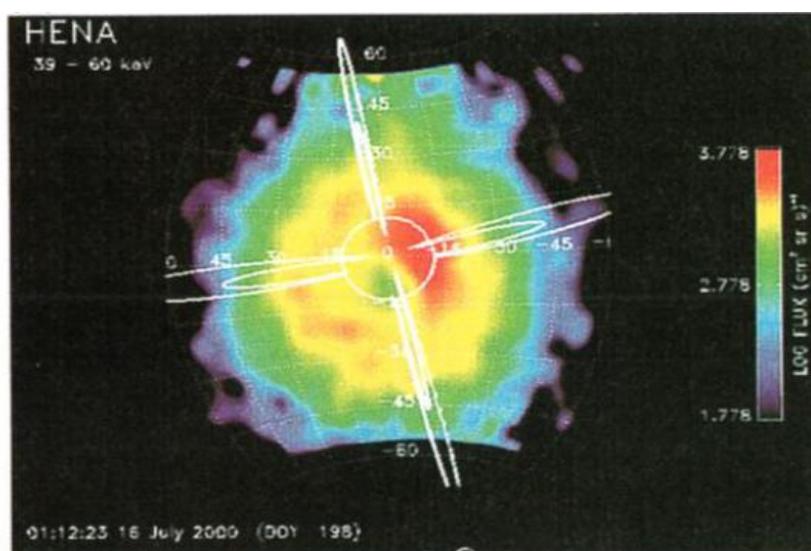


Figure 1. HENA ENA ring current emission 0112UT July 16, 2000. (a) Image from above the Earth's north pole. This vantage point provides a fairly undistorted view of the local time distribution of ENA emission. (High pixel fluxes along the top edge result from an instrument artifact.) (b) Same data as (a), in array of pixel values. (c) Same as (a), but pixels are smoothed.

图 1.20: HENA ENA 环电流 (2000 年 7 月 16 日 0112UT)

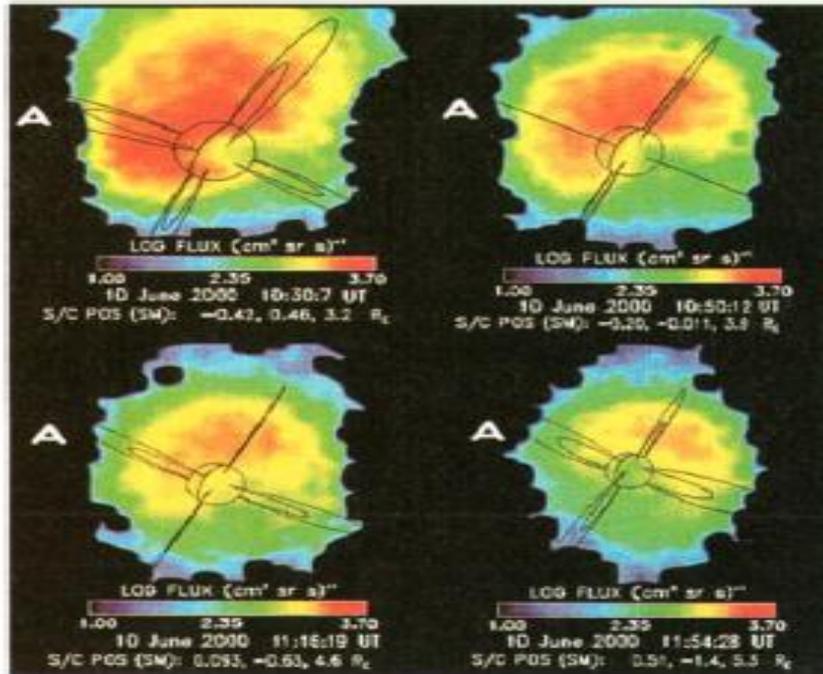


Figure 3. Sequence of images from June 10, 2000 storm of ENA emission at 16 to 27 keV (assuming hydrogen). Although the spacecraft moves within its orbit over the 1.5 hours covered by this sequence, the viewing perspective changes little enough that the gradient/curvature drift of the parent ion population can be followed. Over this period, the pattern rotates clockwise about the Earth by $\sim 90^\circ$. The rectangular scallops along the edges of some images are smoothing artifacts equal in linear dimension to 2 adjacent pixels (roughly the size of two pixels at this energy). Peak pixels contain about 100 counts.

图 1. 21: HENA ENA 地磁暴 (2000 年 7 月 10 日)

1.2.9. 磁层对“巴士底”事件的响应分析

Raeder 等 (2001, *Solar Physics*, 204, 325-338) 分析了“巴士底”磁暴期间太阳风与地磁层、电离层和热层的相互作用，磁暴引起磁层被极大压缩和侵蚀，造成 3 颗 GOES 同步卫星在相对长时间进入磁鞘。

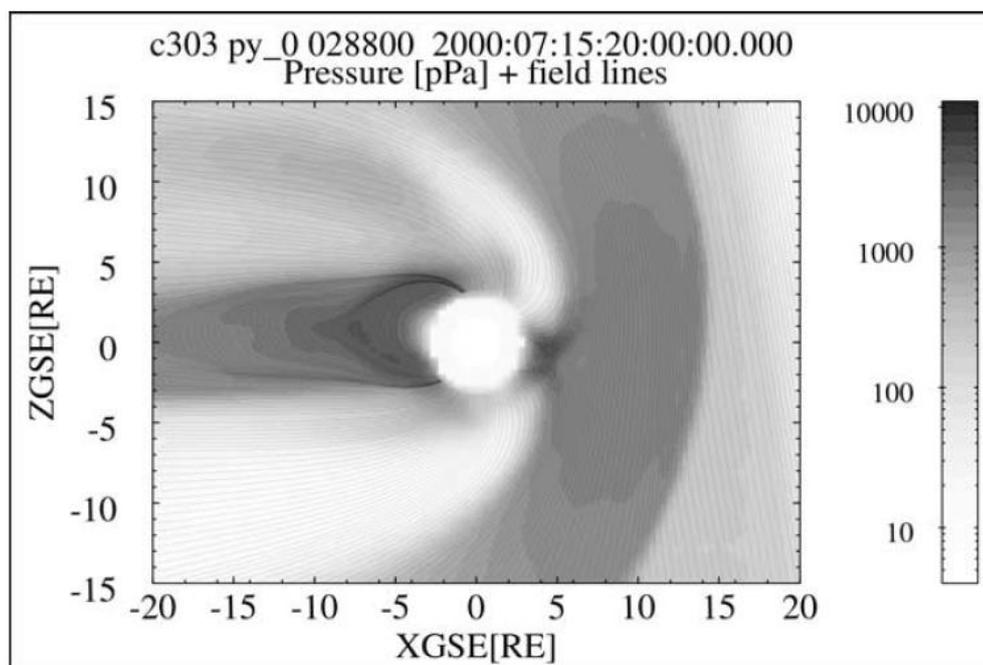


Figure 3. Cut of the noon-midnight meridional plane shows the plasma pressure in grayscale and magnetic field lines at 20:00 UT on 15 July 2000.

图 1. 22：等离子体压

1.2.10.2000 年巴士底日星际扰动的 ACE 观测

Smith 等(2001, Solar Physics, 204, 229 - 254)分析了包含 2000 年巴士底日六天的 ACE 观测, 包括 ICME 驱动的激波、磁云、激波加速的高能粒子、及太阳高能离子与电子。

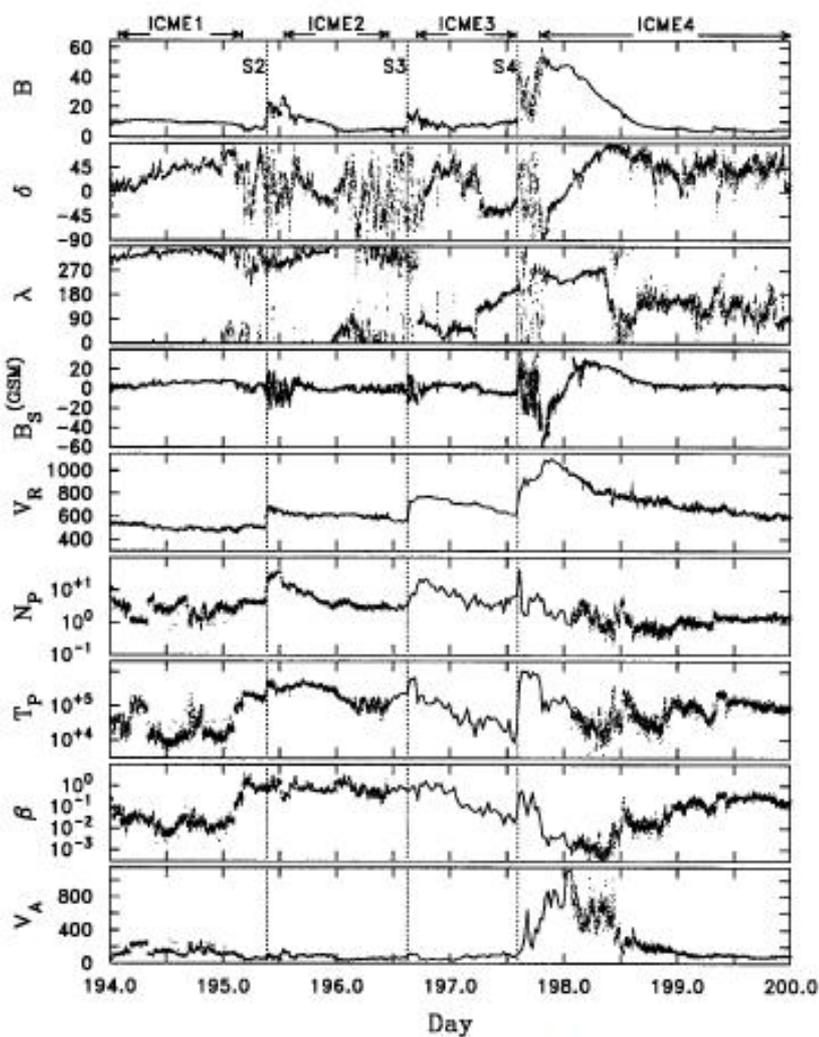


Figure 1. Overview of 6 days surrounding the Bastille Day observations. IMF intensity B (nT), latitude angle δ (deg), and longitude λ (deg) with southward component of the IMF in GSM coordinates B_s^{GSM} . Measured radial component of the wind velocity V_R (km s^{-1}), proton density N_p (cm^{-3}), and temperature T_p (K) are also shown along with computed proton β and Alfvén speed V_A (km s^{-1}). Three shocks (S2, S3, and S4) are marked by vertical dashed lines and 4 ICMEs are marked at top.

图 1. 23: 太阳风观测参数

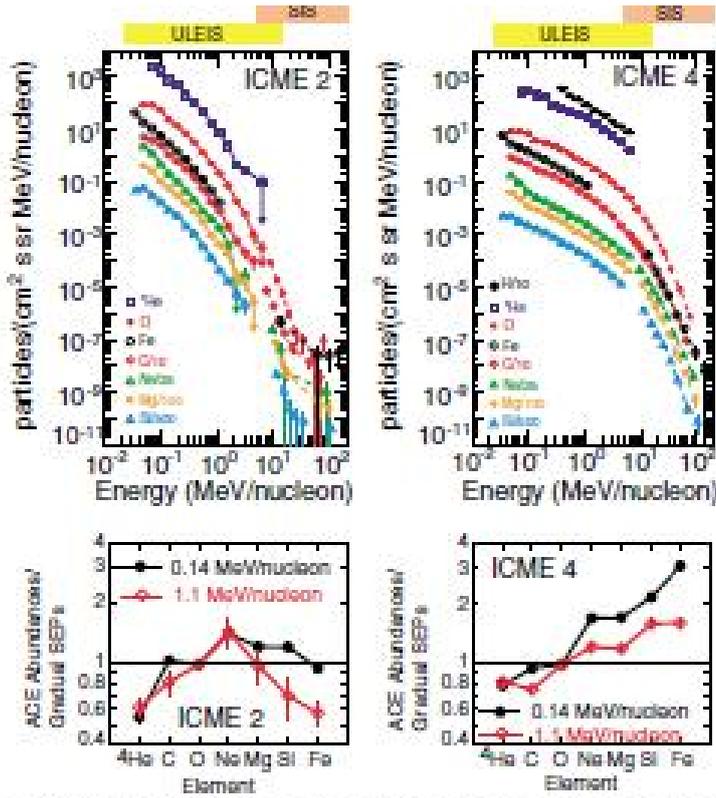


Figure 5. Upper panels: Energy spectra of various ion species measured by ULEIS and SIS (see Section 3.4) during the Bastille Day event. Energy ranges of each instrument are marked at top. Lower panels: heavy ion abundances compared with 4–5 MeV nucl^{-1} abundances measured in gradual SEPs (from Reames, 1999). All abundances are normalized to O. ULEIS abundances are shown at $\sim 0.14 \text{ MeV } \text{nucl}^{-1}$ and $\sim 1.1 \text{ MeV } \text{nucl}^{-1}$. The left and right panels show data from ICME2 and ICME3.

图 1. 24: ULEIS 及 SIS 观测的各种离子能量谱 (上)、重离子丰度 (下)

1.2.11. 日球层激波扰动预报模型

Dryer 等 (2001, Solar Physics, 204, 267-286) 综合利用三个模型来分析日球激波在日地空间的传播并实时预报到达地球的时间: STOA (Shock Time of Arrival), ISPM (Interplanetary Shock Propagation Model) 和 HAFv.2(Hakamada - Akasofu - Fry version 2.0)。

表 1.5: “巴士底”耀斑事件

TABLE I
The ‘Bastille Epoch’ solar events that preceded, included, and followed the 14 July 2000 flare.

Event No.	FF # ^a	FF date (hr)	Day	Start time (UT)	Radio burst type	Shock speed (km s ⁻¹)	V _{sw} (km s ⁻¹)	Flare		τ (hr)	CME _{fast} V _{max} (km s ⁻¹)
								Location	Classification		
1	176	7	7	0118	m II	700	380	N21 W17	F50 ^b	0.50	none
2	177	8	7	1114	m II	800	300	N23 W41	C5.6X0 ^b	2.00	405
3	178	19	7	2055	m II	1000	370	N18 W6	X7	0.50	none
4	179 ^c	28	9	1117	m II	800	450	S19 W07	F7	0.25	1623
5	180	24	10	2125	m II	1300	450	S18 W5	M5.0M10	2.50	none
6	181 ^d	16	11	1510	4-b II	1200 ^e	500	S16 W0	X1.0M10	3.00	1040
7	182 ^e	21	12	0107	m IV	1000 ^f	400	S17 W7	X1.0M10	0.70	none
8	185	8	12	2014	m II	650	480	S17 W6.5	X50	0.70	1775
9	184	30	14	1020	m II	1000 ^g	750	N22 W17	X0.7M10	1.50	none
10	185	20	15	1403	m II	700	600	S19 W11	X50	0.25	none

Definitions and explanations: ^a indicates that a proxy input was used for this run. This is shown in the FF run number, and also with the parameter that is estimated, as FF = Ferret Forecast number used in real-time study program that started in February 1997 (mailings began August 1998 and are continuing). At this writing, the latest occurrence is FF0504 (25 August 2000). ^b = time elapsed since previous event, in hours, m II = metric type II radio burst, 4-b II = decametric type II radio burst, m IV = metric type IV radio burst. Shock speed is estimated from the metric type II radio bursts, except for ^c events. Here, the CME speed is used as a guide. For Event #9, the reported type II velocity was adjusted in real time, guided by the V_{max} ^h in the classification means that its formation was not available in real time. V_{sw} = speed of the solar wind at 1 AU, from ACE, used for the background solar wind in STOA. τ = duration of shock driver, estimated from the 1–8 Å X-ray flux. CME_{fast} = real time information from SOHO/LASCO of halo (P = partial halo) CMEs; V_{max} = CME speed in plane of the sky (position angle is not listed here).

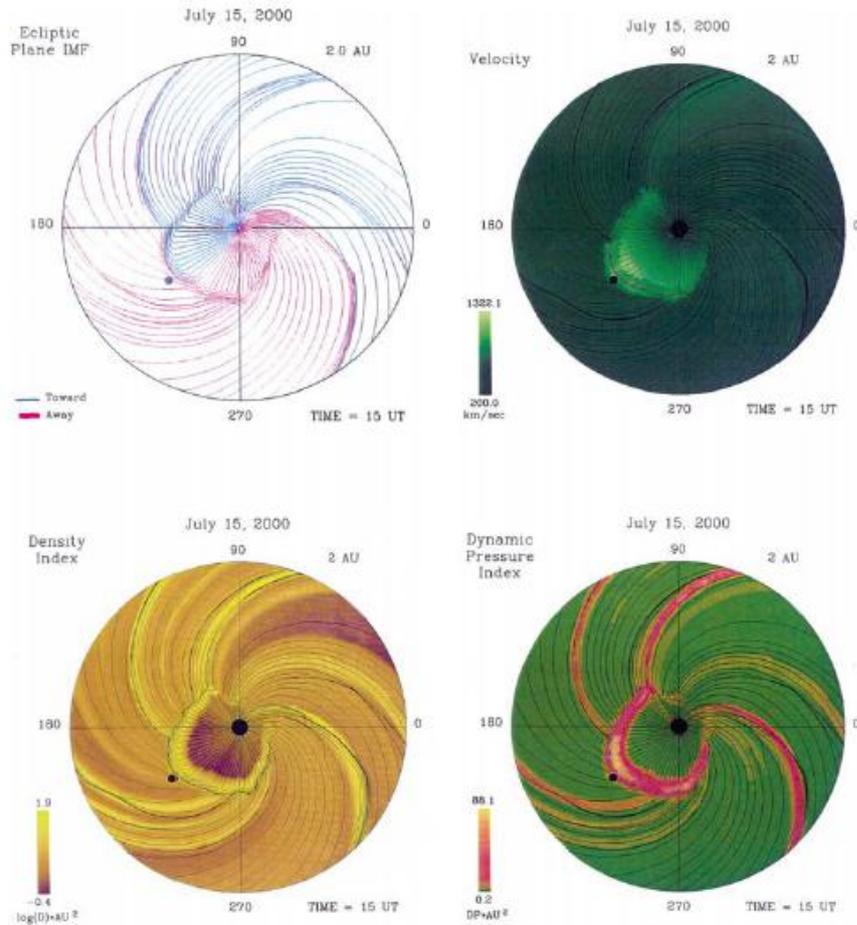


Figure 2. Real-time ecliptic plane plots of basic solar wind and IMF parameters from the HAFv.2 model at 15:00 UT, 15 July 2000, following the Bastille Day solar flare on 14 July 2000. Earth is represented by the black dot and the outer circle is at 2 AU. Upper left panel: IMF lines (blue, toward Sun; red, away). Upper right panel: solar wind plasma speed. Lower left panel: solar wind proton density (D) normalized as indicated in the scale. Finally lower right panel: dynamic pressure, DP , normalized as indicated in the scale.

图 1. 25: 太阳风与行星际磁场参数

1.2.12. 跨赤道暗条爆发研究

汪景琇等（2006, ChJAA, 6, 247-259）认为“巴士底”全晕耀斑/CME 事件是由跨赤道暗条爆发引起，而不是仅仅一个活动区的作用结果。

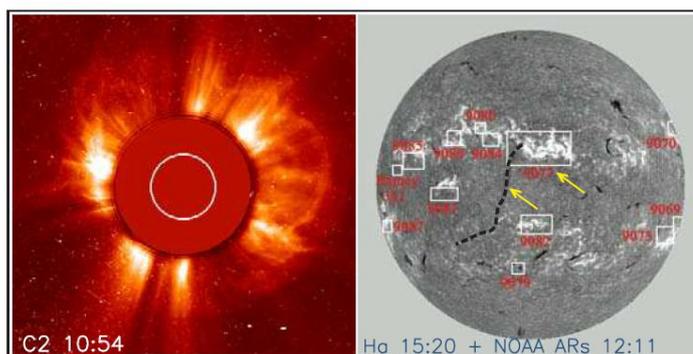


Fig. 1 Left: LASCO C2 image showing the Bastille CME on 2000 July 14, at 10:54 UT. Seen are internally linked and braided complex structures. Right: the NOAA numbers of Ramey sunspot at 12:11 UT are overlaid on an H α image at 15:20 UT showing the CME's source regions as indicated by the two arrows. The dashed line marks the eruptive transequatorial filament associated with the CME.

图 1. 26: LASCO C2 图像与 H α 图像

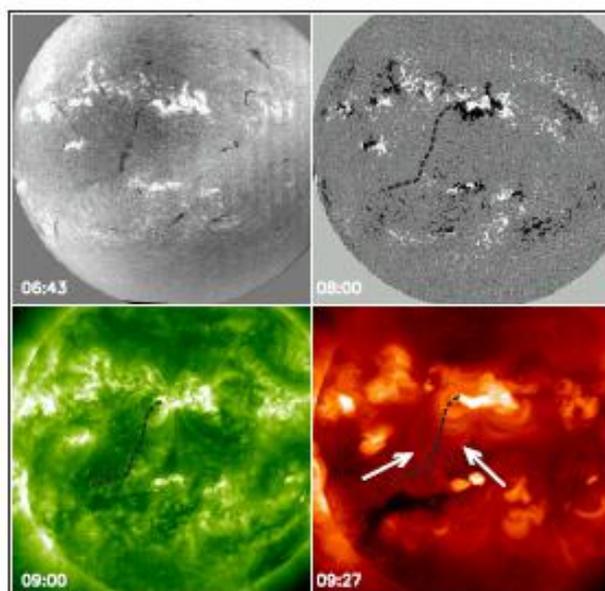


Fig. 2 A Huairou H α filtergram (upper-left) shows a huge transequatorial filament, to which active region filaments in AR.9077 and AR.9082 are joined. The dashed lines in the other three panels mark the transequatorial filament. Arcades straddling the huge filament are seen clearly in an SOHO EIT 195 \AA image (lower-left) as well as in a Yohkoh SXT image (lower right, see arrows). Magnetic flux distribution is shown by the SOHO MDI magnetogram (upper-right).

图 1. 27: 跨赤道暗条: 怀柔磁图 (左上)、SOHO EIT 195 \AA (左下)、Yohkoh SXT (右下)和 SOHO MDI 磁图(右上)

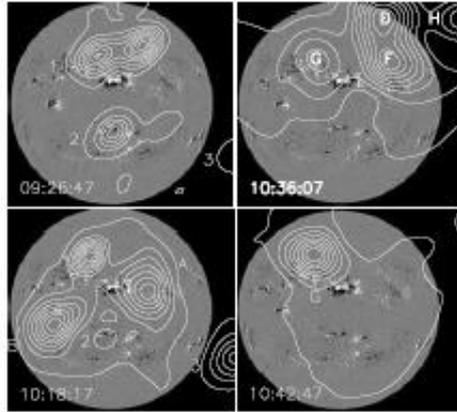


Fig. 7 Radio emission sources at 164 MHz obtained from NRH superposed on the MDI magnetograms at the closest time. Pre-event Type I storm sources are numbered as '1', '2', '3', and burst sources are denoted by capital letters. They encompassed almost the entire range of longitude and a huge span of longitude, which indicate that multiple-flux systems were involved in the CME development. The angular resolution of the NRH is $5.5' \times 3.2'$ at 164 MHz.

图 1. 28: NRH 164MHz 射电辐射源与 MDI 磁图叠加

1.2.13. 哨声模式声波与地磁暴的关系分析

Smith 等 (2004, JGR, 109, A02205) 利用哈利站 VLF/ELF Logger Experiment (VELOX), 分析了哨声模式声波 (whistler mode chorus waves) 与地磁暴的关系, 两者还是有一定的关系。

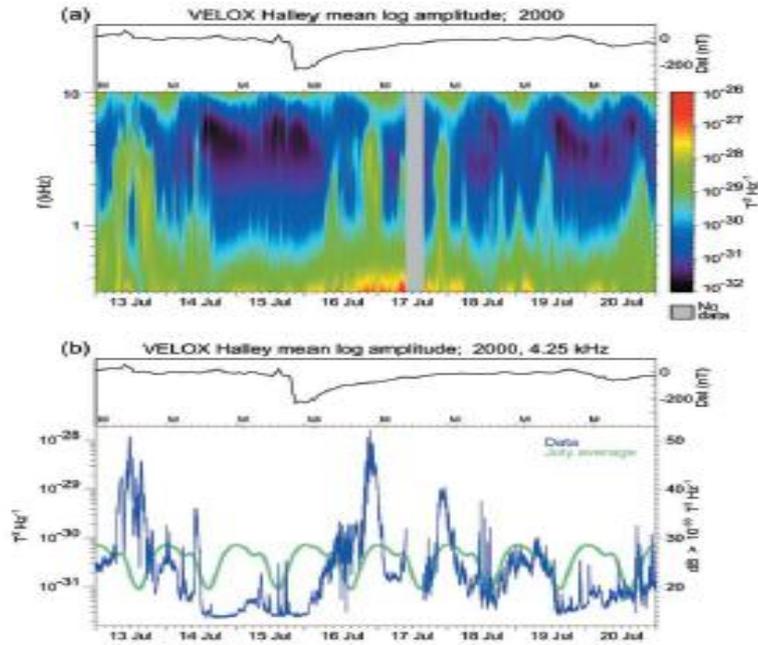


Figure 2. (a) Halley ELF/VLF spectrogram from the VELOX instrument for 13–20 July 2000, covering the time of the “Bastille Day” storm. The Dst index is shown above. (b) Wave intensity in the 4.25 kHz VELOX channel, plotted on the same timescale as Figure 2a, is shown by the blue curve. The green curve is the average behavior for July for the years 1992–2002. The left-hand scale is logarithmic in wave magnetic field spectral density, expressed in units of $T^2 \text{ Hz}^{-1}$, while the right-hand one shows the conventional decibel scale relative to $10^{-30} T^2 \text{ Hz}^{-1}$.

图 1.29: 哈利 ELF/VLF 谱暴与 VELOX 4.25 kHz 波强

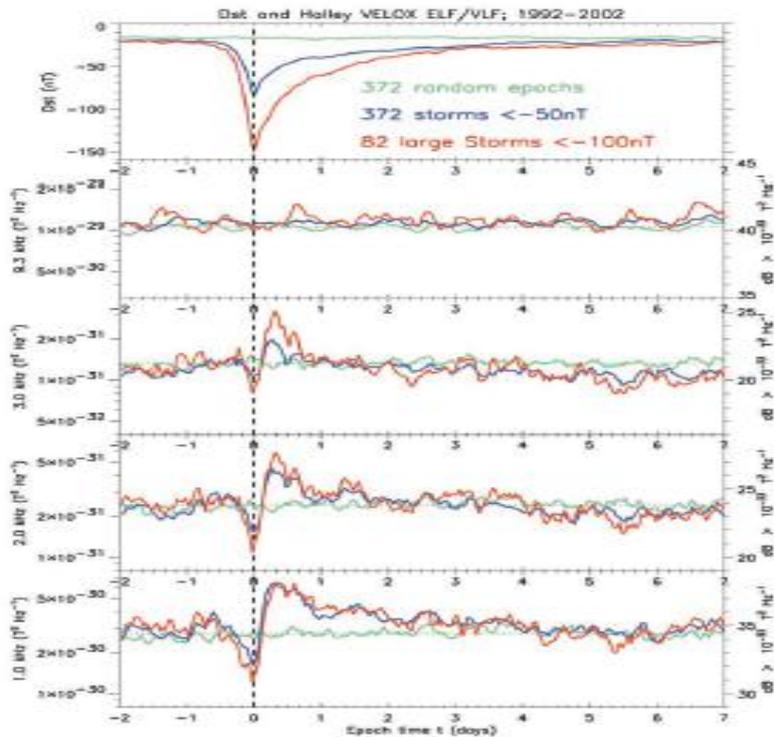


Figure 4. Superposed epoch plots, constructed as described in the text, for 372 storms in 1992–2002 (blue traces) and 82 large storms (red traces). The green trace is for 372 randomly chosen epochs in 1992–2002. The VELOX channel wave amplitudes for three chorus band frequencies (1.0, 2.0, 3.0 kHz) and one monochorus frequency (9.3 kHz) together with the Dst index are shown for a range of epoch times from $t = -2$ days to $t = +7$ days. The y scales are as in Figure 2a.

图 1.30: 地磁暴与三个 VELOX 波幅

1.2.14.射电爆发研究

Karlicky 等 (2001, A&A 369, 1104-1111) 利用怀柔站太阳射电谱 Solar Radio Broadband Fast Dynamic Spectrometers (1 - 2, 2.6 - 3.8, and 5.2 - 7.6 GHz) 和 Ondrejov 站的 0.8 - 2, 2 - 4.5 GHz 谱, 研究了“巴士底”事件期间四个最强耀斑的射电频谱。发现飘移脉冲结构是这些耀斑的典型特征, 还发现了许多其他精细结构, 如窄带飘移线、斑马纹形状的飘移谐波结构、窄带分米尖峰的飘移分支、快速正和负飘移暴结构。

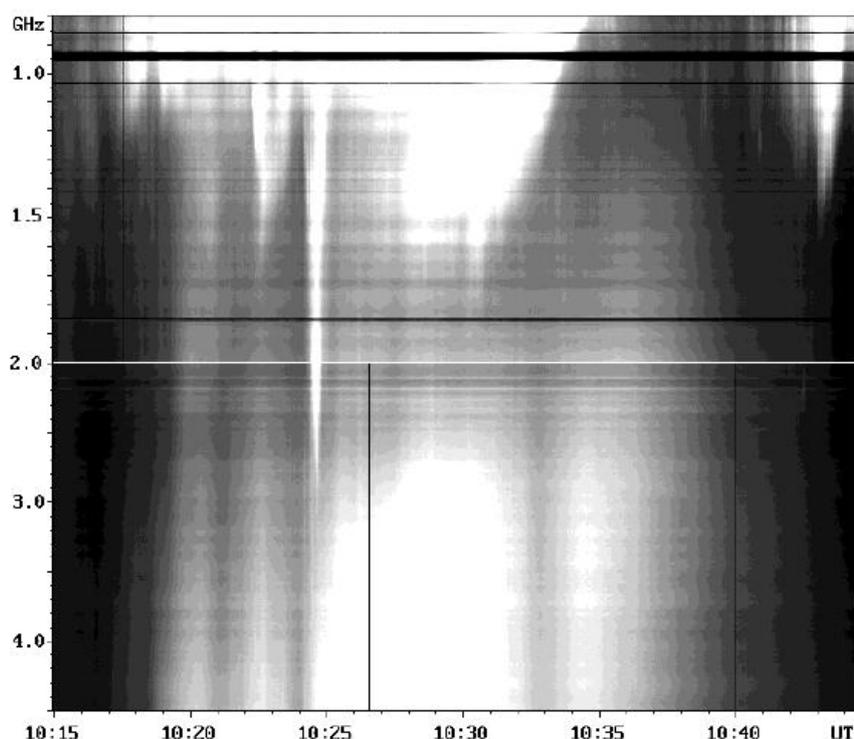


Fig. 10. The 0.8–4.5 GHz overview radio spectrum with a drifting continuum observed on July 14, 2000 by the Ondřejov radiospectrographs

图 1. 31: 0.8 - 4.5 GHz 射电谱

Reiner 等(2001,Solar Physic, 204, 123 - 139)利用搭载在 WIND 上的 WAVES 射电仪 (4.0876 kHz to 13.825 MHz), 研“巴士底”事件期间 I 型、II 型和 III 型射电暴。

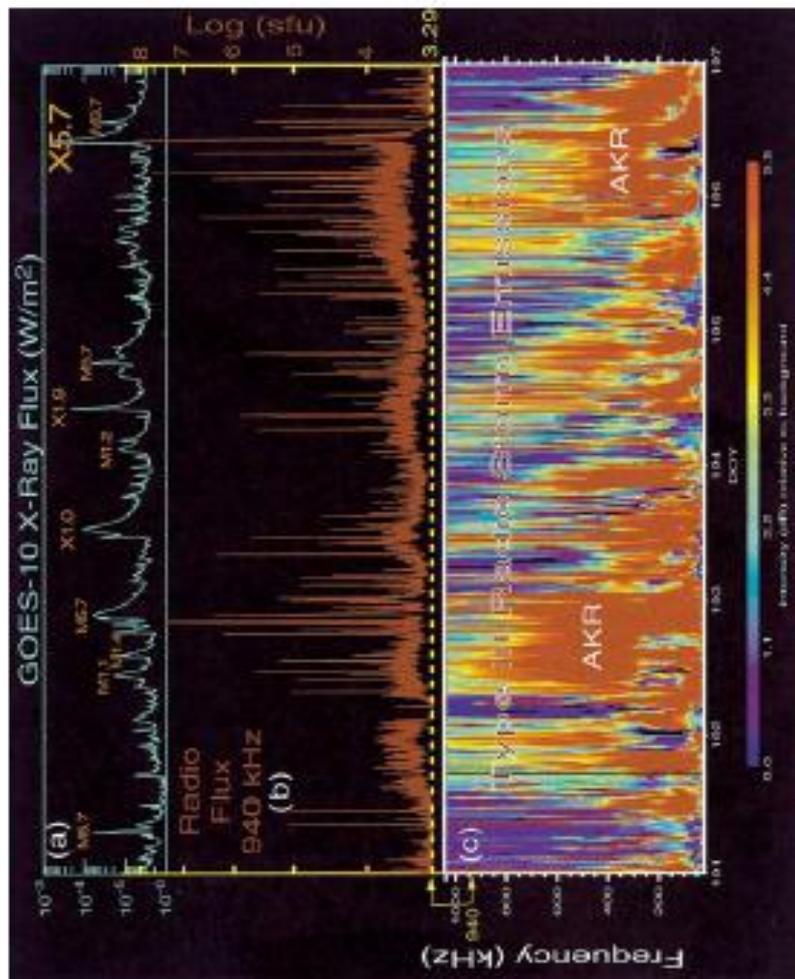


Figure 1. Overview of the WIND/WAVES radio data from 9–14 July 2010. (a) The GOES X-ray flux during this time period. (b) The intensity (\log (sf.u.)) of the radio emission at 940 kHz. (c) Dynamic spectrum of the radio emission. The frequency range is from 20 to 1040 kHz.

图 1.32: 耀斑与射电暴

1.2.15. 与比邻星耀斑比较

Reale 等 (2004, A&A 416, 733 - 747) 利用 XMM-Newton/EPIC-PN0n 对比邻星 (Proxima Centauri) 的观测数据, 对比邻星耀斑和 Bastille Day 耀斑进行了比较。两个环系统的加热函数非常像: 在环足点处的强脉冲及随后环在日面部分的缓变衰变, 这意味着这种形状在太阳及恒星耀斑中可能非常普通。

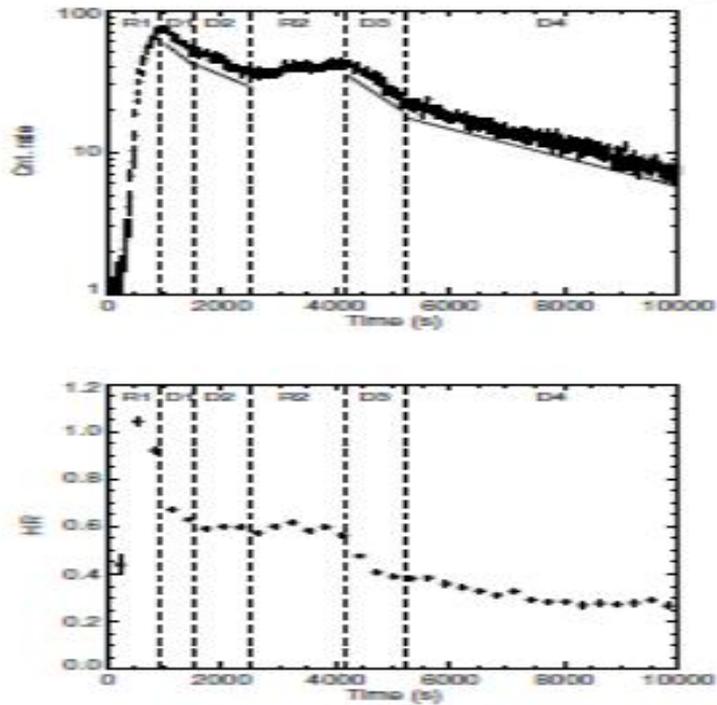


Fig. 1. Upper panel: light curve (10 ks) of the flare on Proxima Centauri on 12 August 2001 as detected with the XMM-Newton EPIC-PN detector in the 0.15–10 keV band. The flare can be segmented into six phases, two rising (R1, R2) and four decay ones (D1–D4), bounded by the vertical dashed lines. The solid lines mark the decay trends. Time $t = 0$ corresponds to 17:00 UT of 12 August 2001. Lower panel: hardness ratio (ratio of 1–4.5 keV to 0.4–1 keV count rates) in the same time interval as the light curve. Time resolution is 300 s.

图 1. 33: 比邻星耀斑光变曲线



Fig. 8. Sketch of the possible scenario of the flaring loop system on Proxima Centauri scaled to the Bastille Day flare on the sun. The size of Proxima Centauri and the flare loops are on scale.

图 1. 34: 比邻星的耀斑环系

1.3. 主要科学贡献

“巴士底”大耀斑 (X5.7) 事件期间伴随全晕 CME 及高能粒子事件, 并产生了大地磁暴 ($Dst = -300nT$) 及突然电离扰动 (S3 辐射风暴), 在日地空间各个波段都能观测到其影响, 因此, 该事件是研究光球、日冕层、日地空间、地磁层、电离层等各个领域的一个极佳事件案例, 是研究大耀斑、活动区磁场非势性、跨赤道暗条、CME 间相互作用、大磁暴等现象的一个典型代表事件, 对研究日地空间各个领域中的极端物理现象的各个物理量都起到了促进作用, 在对耀斑爆发物理触发机制的理论研究也起到了举足轻重的重要作用, 尤其是对由太阳爆发事件引起的空间灾害事件的研究与应用的重视程度。

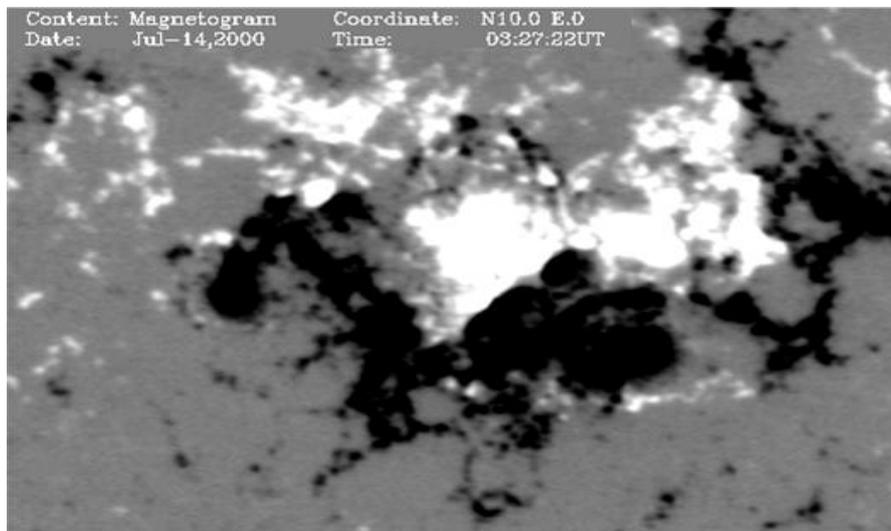


图 1.35: NOAA 9077 活动区磁图(怀柔磁场望远镜观测, 0.5 角秒/像素)

● 多波段成像综合分析研究

“巴士底”事件提供了一个利用多种天基及地基仪器观测的数据进行综合分析的一个极佳案例。

● 物理现象及参量研究

➤ 磁对消与暗条爆发

发现事件过程中唯一明显的磁场变化是在暗条附近许多地点的磁对消。此

外，暗条的所有初始扰动及暗条周围的初始变亮都发生在对消点。

➤ 太阳耀斑中的磁绳结构及相关高能过程

发现了磁绳存在，磁绳位于暗条暗条中性线上方，磁绳的磁力线绕绳转动超过 3 圈，具有不同方向的多层磁拱覆盖其上，这种磁场结构对于解释 $H\alpha$ 、EUV 及射电观测到的高能耀斑过程提供了一个有利的模型。

● 运动与机制研究

➤ 高能粒子的重离子能谱由激波加速引起

研究了“巴士底”事件期间高能粒子的重离子 (Fe) 能谱的特殊性，铁能谱近似幂律分布，而其他则为指数分布，认为是由双源激波加速引起的。

➤ 黑子演化研究

(1) 特殊的磁性形态和快速连续的碎裂导致活动区始终处于高剪切状态；
(2) 一个黑子群的运动方向与暗条被切断并激活的位置之间存在良好的空间对应关系；
(3) 快速浮现磁通系统的运动特征显示黑子运动和最大耀斑之间有良好的相关性，表明在 7 月 14 日双带耀斑初始是由通量系统的连续浮现促成的。

➤ 三维磁重联研究

“巴士底”耀斑可能是由日冕分割线处的三维磁重联引起，磁分割面的运动由两种运动导致。一种是平行于光球中性线的剪切流动，另一个是指向中性线的汇聚流动。

➤ 活动区非势性演化分析

(1) 剪切角在暗条通道发生了巨大的变化；(2) 大耀斑事件前电流系统破坏形成新的弱系统；(3) 耀斑前源场和磁能减弱。

➤ 与比邻星耀斑比较:两个耀斑环分量及两个加热机制

对比邻星耀斑和 Bastille Day 耀斑进行了比较。两个环系统的加热函数非常像：在环足点处的强脉冲及随后环在日面部分的缓变衰变。

● 射电研究

➤ 射电爆发研究

研究了“巴士底”事件期间四个最强耀斑的射电光谱。发现飘移脉冲结构是

这些耀斑的典型特征，还发现了许多其他精细结构，如窄带飘移线、斑马纹形状的飘移谐波结构、窄带分米尖峰的飘移分支、快速正和负飘移暴结构。

➤ 射电暴研究

研究了“巴士底”事件期间 I 型、II 型和 III 型射电暴。

● CME 特性及其传播

➤ 跨赤道暗条爆发与 CME

认为“巴士底”全晕耀斑/CME 事件是由跨赤道暗条爆发引起，而不是仅仅一个活动区的作用结果。

➤ 日球层激波扰动预报模型

综合利用三个模型: STOA, ISPM 和 HAFv.2 来分析日球激波在日地空间的传播并实时预报到达地球的时间。

● 对地效应

➤ “巴士底”大磁暴

比较了两个地磁暴，一个“巴士底”大磁暴（2000 年 7 月 15-16 日, $Dst = -300nT$ ），另一个是小磁暴(2000 年 7 月 10 日, $Dst = -55nT$)，小磁暴中引起 Dst 变化的离子基本是在开放飘移路径，而大磁暴中引起 Dst 变化的离子重要是在封闭飘移路径。

➤ 磁层对“巴士底”事件的响应分析

分析了“巴士底”磁暴期间太阳风与地磁层、电离层和热层的相互作用，磁暴引起磁层被极大压缩和侵蚀，造成 3 颗 GOES 同步卫星在相对长时间进入磁鞘。

➤ 巴士底日星际扰动的 ACE 观测

分析了包括 2000 年巴士底日六天的 ACE 观测，包括 ICME 驱动的激波、磁云、激波加速的高能粒子、及太阳高能离子与电子。

➤ 哨声模式合唱波与地磁暴的关系分析

分析了哨声模式合唱波（whistler mode chorus waves）与地磁暴的关系，两者还是有一定的关系。

1.4. 其它

1.4.1. 其它相关参考文献

参见第四章 4.2.4.2.13 “万圣节”事件与“巴士底”事件比较研究, p.错误!
未定义书签。

1.4.2. 影像观测资料

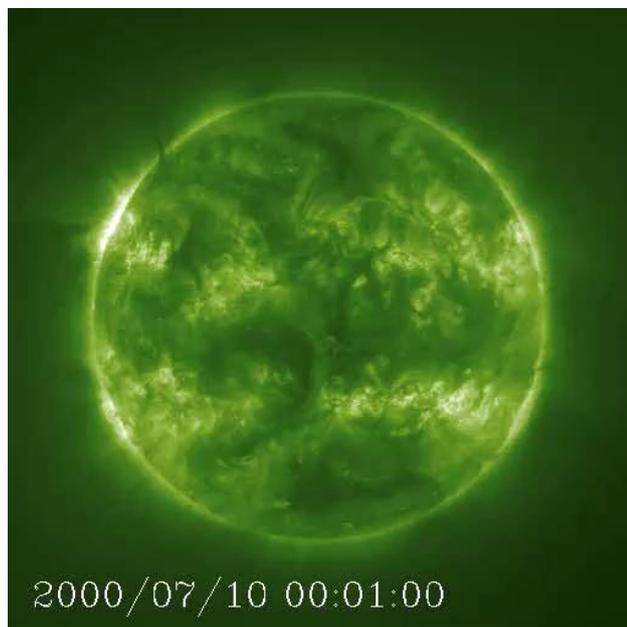


图 1. 36: SOHO/EIT 动态原始影像(Andrews, 2001, Solar Physics, [204, 181-198](#))

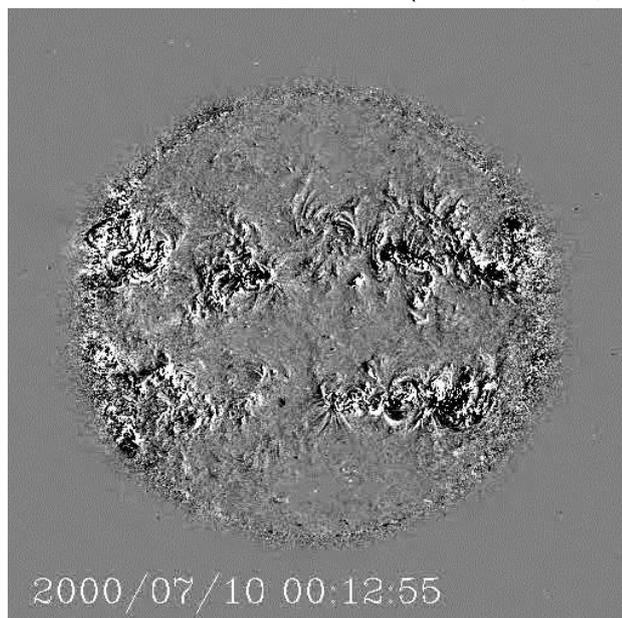


图 1. 37: SOHO/EIT 动态较差影像(Andrews, 2001, Solar Physics, [204, 181-198](#))

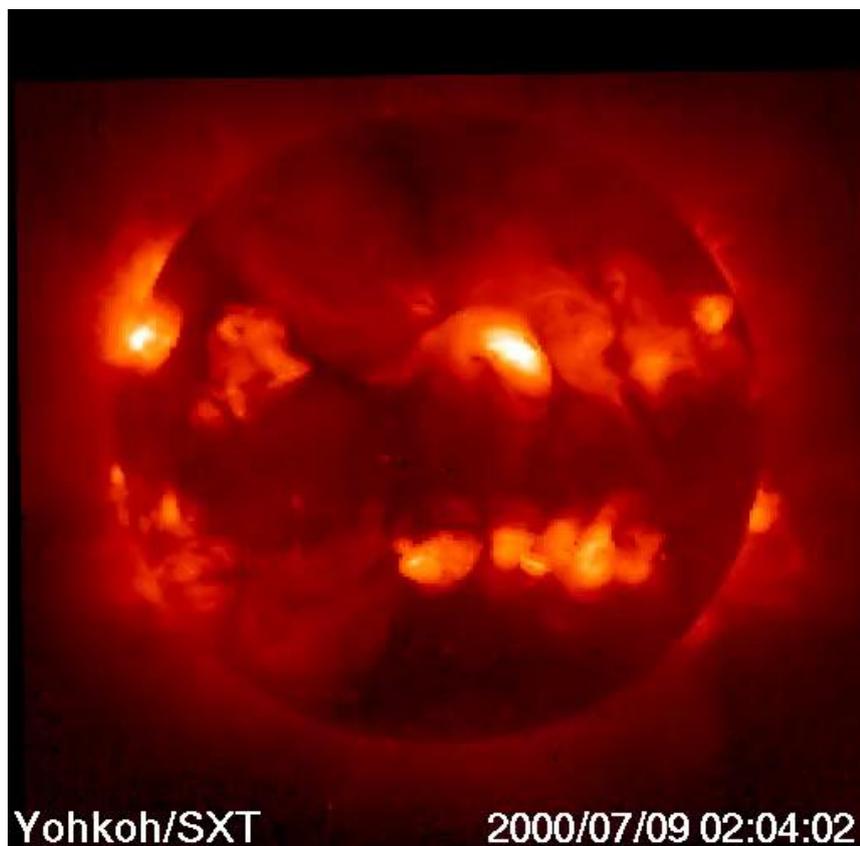


图 1. 38: Yohkoh/SXT 动态影像(Andrews, 2001, Solar Physics, [204, 181-198](#))

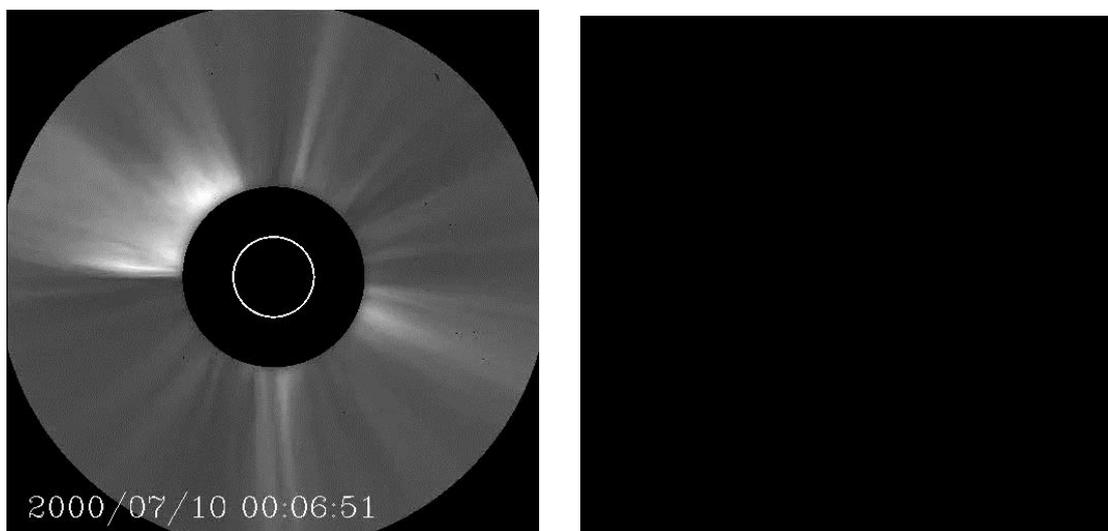


图 1. 39: SOHO/LASCO 动态影像资料(Andrews, 2001, Solar Physics, 204, 181-198) [C2/ C3](#)

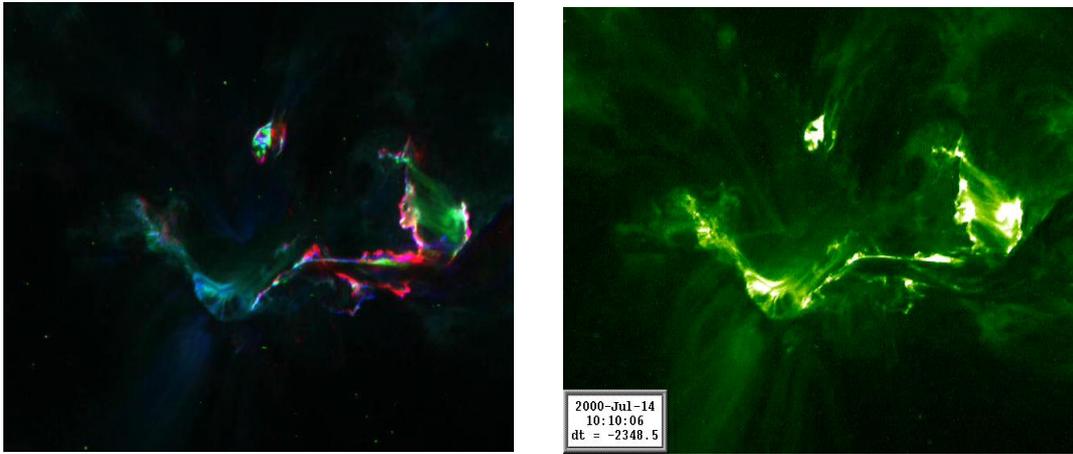


图 1. 40: TRACE 卫星极紫外成像 ([蓝色:171 埃](#); [绿色:195 埃](#))

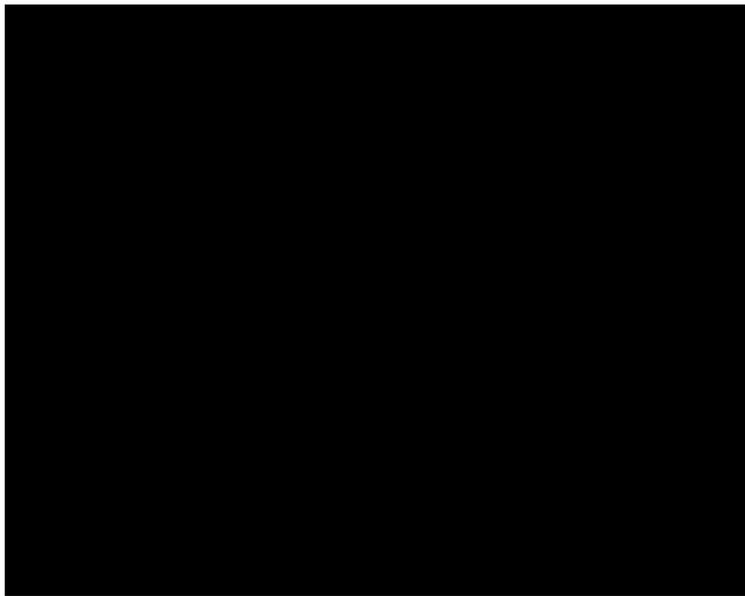


图 1. 41: Bastille Day 耀斑[怀柔 Halpha](#) 影像资料

1.5. 主要参考文献

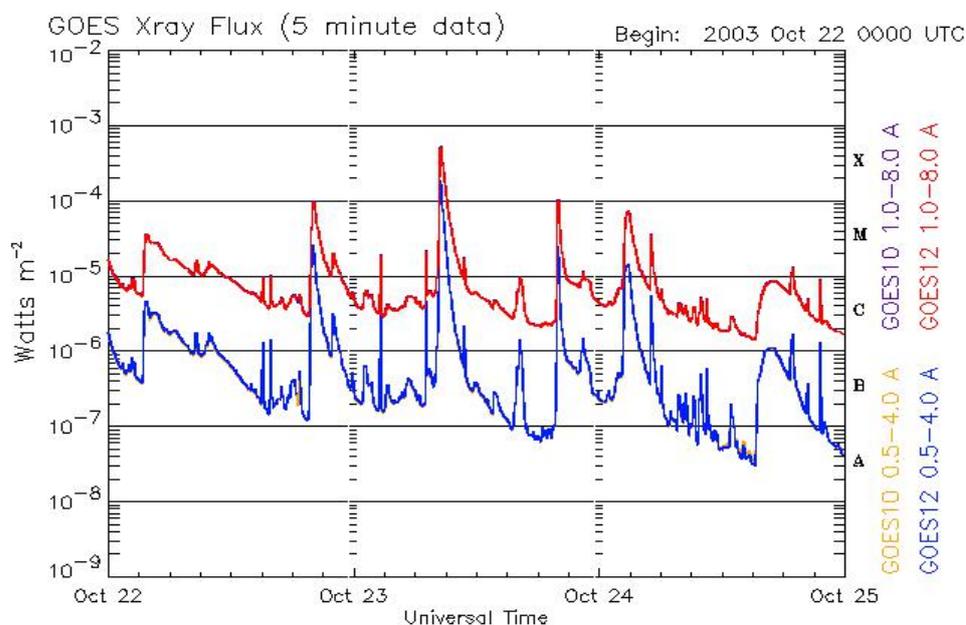
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第二章 NOAA10484 活动区（万圣节）事件

从2003年10月19日到2003年11月5日在太阳上出现了三个活动区 NOAA 10484、10486 和 10488，在此期间三个活动区发生了一系列太阳耀斑、CME，统称为“万圣节（Halloween）”事件。在第二、三、四章分别介绍三个活动区的有关空间天气事件。本章简单介绍 NOAA 10484 活动区，该活动区于2003年10月19日出现（N05E68），10月31日消失（N01W95），10月23日达到最大（N04E13），最大时日面面积1750，磁位型为 $\beta\gamma\delta$ ，该活动区产生了2个X级耀斑、17个M级耀斑，最高级别为X1.2，该耀斑为限制性的，没有形成大的爆发现象。

2.1. 事件概述



Updated 2003 Oct 24 23:56:04 UTC

NOAA/SEC Boulder, CO USA

图 2. 1: 2003 年 10 月 22-25 日 GOES 软 X 射线流量图

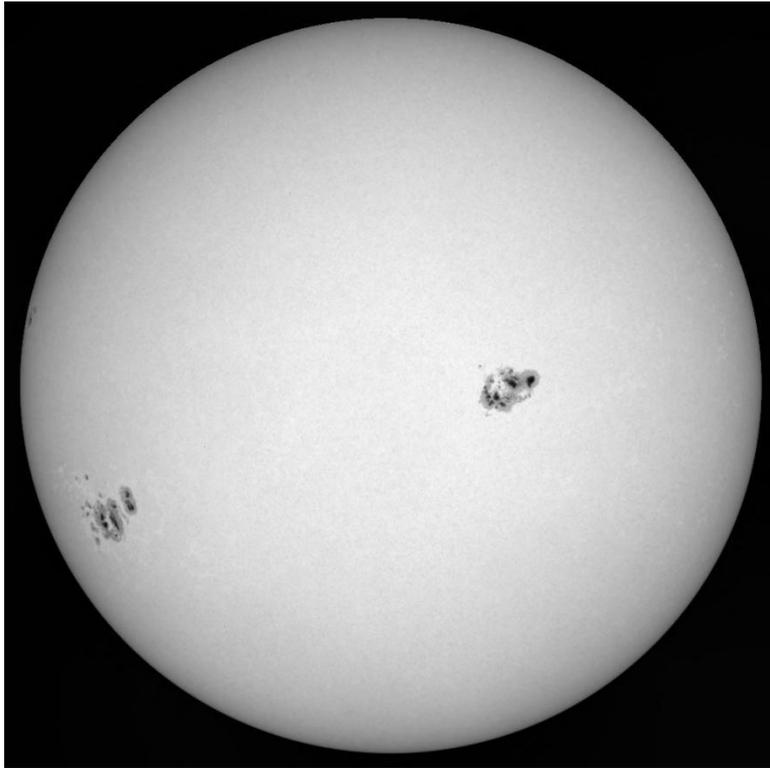


图 2. 2: NOAA10484 活动区全日面黑子图 (2003 年 10 月 25)

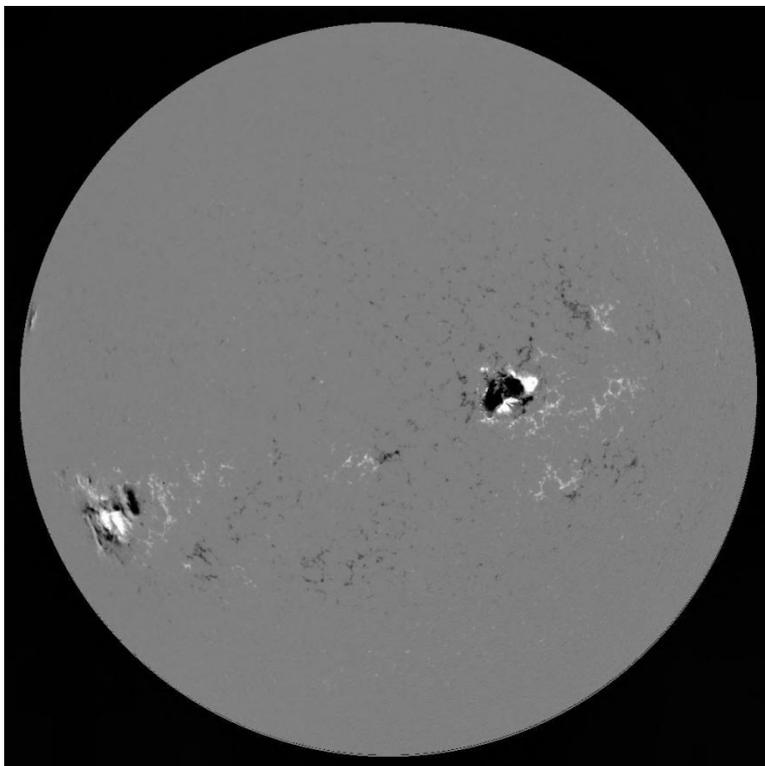


图 2. 3: NOAA10484 活动区全日面 SOHO、MDI 磁图 (2003 年 10 月 25 日)

2.1.1. 事件特征

- 事件观测时间：2003 年 10 月 19 日出现（N05E68），10 月 23 日达到最大（N04E13），10 月 31 日消失（N01W95）。
- 最大面积：1750 日面单位；位置：N04E13；时间：2003 年 10 月 23 日
- 磁位型： $\beta\gamma\delta$
- X 级耀斑数量：2
- M 级耀斑数量：17
- 最大耀斑级别：X1.2；时间：2003 年 10 月 26 日 17: 33UT，位置：N02W38
- CME 事件：只发生一次窄 CME（10 月 23 日）。

2.1.2. 观测特征

NOAA10484 耀斑是一个限制耀斑，并没有形成大的爆发现象，仅在 2003 年 10 月 23 日 02:41 UT 发生的 M2.4 耀斑伴随窄 CME，2003 年 10 月 25 日发生了 III 型射电暴。在上述三个活动区存续期间的一些现象常常混在一起，或者源区不好准确辨认。

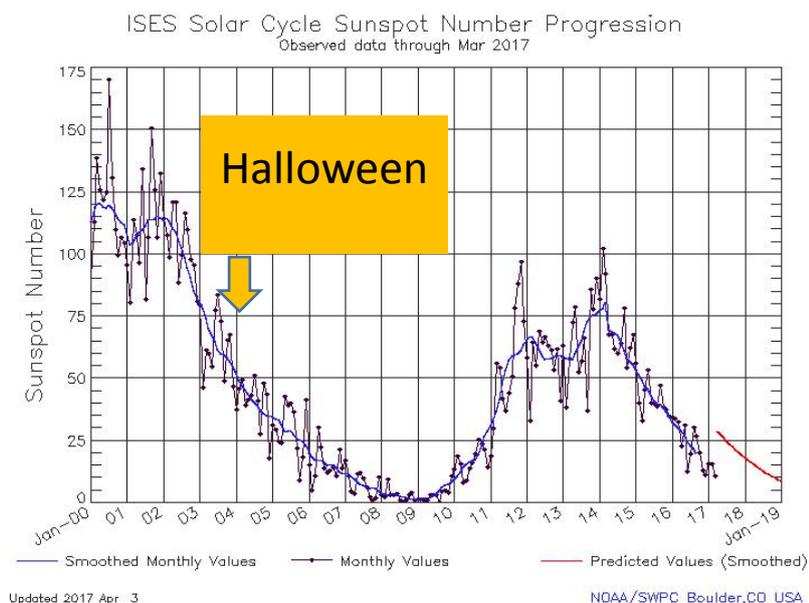


图 2.4：“万圣节”事件出现在活动周的下降段

2.2. 相关事件案例研究

在“万圣节”事件中, NOAA10484 活动区不是很强的活动区, 与 NOAA10484 活动区相关的研究论文发表二十几篇, 与太阳物理相关的不过十来篇, 其中还有部分是“万圣节”事件三个活动区 NOAA 10484、10486 和 10488 的联合研究, 主要是由于与其他两个相比, NOAA10484 活动区活动强度不是很强, 产生的耀斑较少且不是很强, 并无明显的日地效应。

2.2.1. 怀柔站观测到的三个超级活动区

Zhang 等 (2003, Chin. J. Astron. Astrophys., 3, 491 - 494) 分析了怀柔观测站的多通道太阳望远镜观测到的三个超级活动区 (NOAA 10484, 10486 和 10488) 的磁场构型, 认为强剪切与快速磁通浮现可能是这些事件的主要起因。

表 2. 1: 怀柔观测站活动区观测记录

Table 1 List of Observations of Three Active Regions at HSOS

Date	Time (UT)	Measure	Date	Time (UT)	Measure
18	03:00-08:00	L, T, V, H α , H β	26	00:00-06:00	L, T, V, H α , H β
19	23:00-01:00	L, T, V, H α , H β	27	01:00-06:00	L, T, V, H α , H β
20	00:00-02:00	L, T, V, H α , H β	28	00:00-08:00	L, T, V, H α , H β
21	01:00-04:00	L, T, V, H α , H β	29	00:00-08:00	L, T, V, H α , H β
22	00:00-09:00	L, T, V, H α , H β	30	00:00-05:00	L, T, V, H α , H β
23	00:00-07:00	L, T, V, H α , H β	31	03:00-05:00	L, H α
24	00:00-09:00	L, T, V, H α , H β	02	05:00-07:00	L, T, V, H α , H β
25	00:00-08:00	L, T, V, H α , H β	03	03:00-07:00	L, T, V, H α , H β

L: Longitudinal field; T: Transverse field; V: Doppler velocity field.

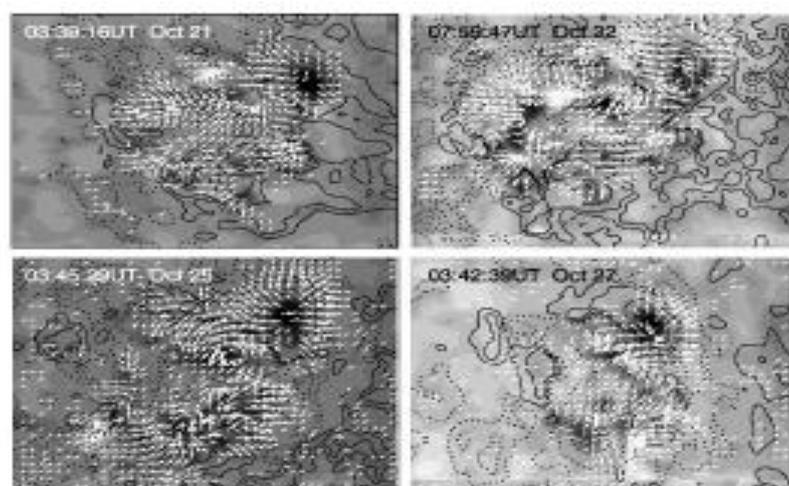


Fig. 1 Photospheric vector magnetograms in NOAA 10484. The solid (dashed) contours indicate the longitudinal field of positive (negative) polarity. The arrows mark the transverse field. The magnetograms of the AR are overlaid with the H β filtergrams. The field of view is 3.75' \times 2.81'. North is at the top and west is to the right.

图 2. 5: 怀柔站观测的 NOAA 10484 活动区光球矢量磁图

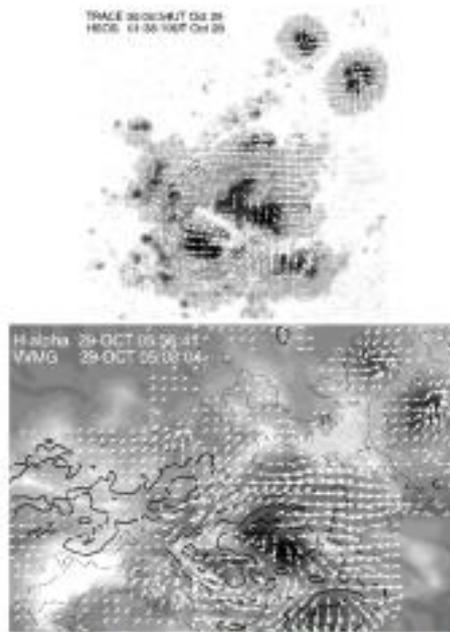


Fig. 2 Photospheric vector magnetic field in NOAA 10486. The solid (dashed) contours indicate the longitudinal field of positive (negative) polarity. The arrows mark the transverse field. The magnetograms of the AR are overlaid with a TRACE white light (upper) and H α (lower) image. The size of the lower image is $4.0' \times 2.7'$.

图 2. 6: 怀柔站观测的 NOAA 10486 活动区光球矢量磁图

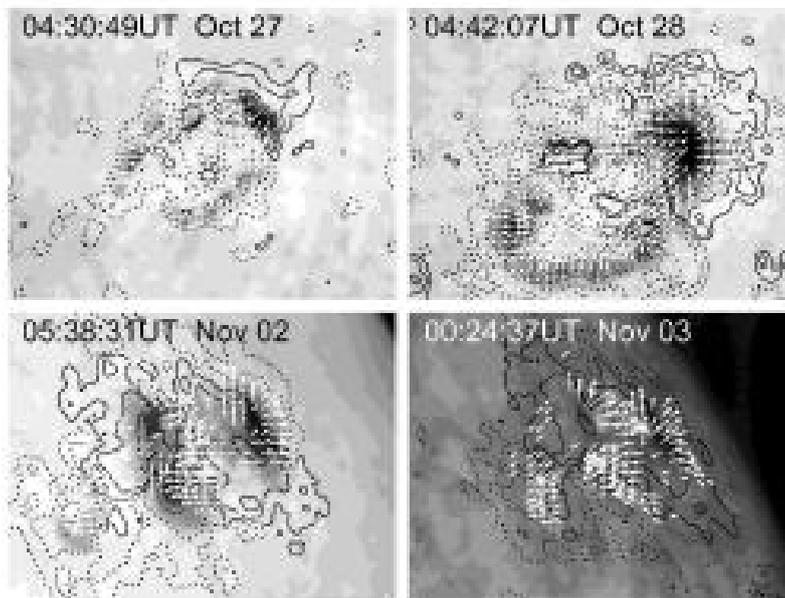


Fig. 3 Photospheric vector magnetograms in the emerging active region NOAA 10488. The solid (dashed) contours indicate the longitudinal field of positive (negative) polarity. The arrows mark the transverse field. The magnetograms are overlaid with the H α image and H β (right bottom) image. The field of view is $3.75' \times 2.81'$.

图 2. 7: 怀柔站观测的 NOAA 10488 活动区光球矢量磁图

2.2.2. 与 2003 年 10 月 25 日 NOAA10484 活动区相关的多重波浪观测

Uddin 等 (2012, APJ, 752, 70) 利用 $H\alpha$, UV (SOHO/EIT) 及射电观测, 对 2003 年 10 月 25 日 NOAA10484 活动区进行了复发冲浪 (surge) 多波段分析, 在每个 surge 底部都发现了与子耀斑相关的几个两结构, 并触发了 III 型射电暴, 大 surge 由形成扇形区域的几束喷流组成, SOHO/MDI 观测显示 surge 前几天 (18-20 日) 在活动区东侧浮现大的二级子。

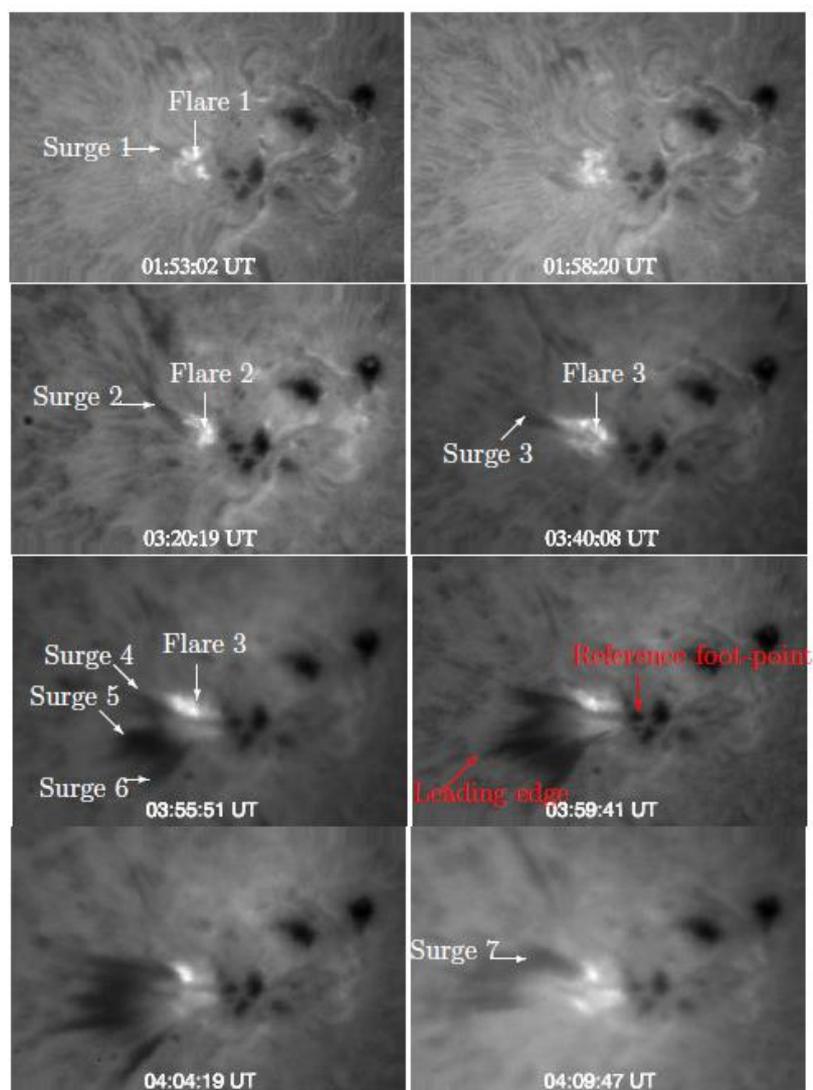


Figure 1. $H\alpha$ image sequence showing the recurrent flare/surge activities on 2003 October 25 in AR 10484. The field of view of each image is $320'' \times 200''$. (A color version of this figure is available in the online journal.)

图 2. 8: $H\alpha$ 图显示复发耀斑/冲浪 (2003 年 10 月 25 日)

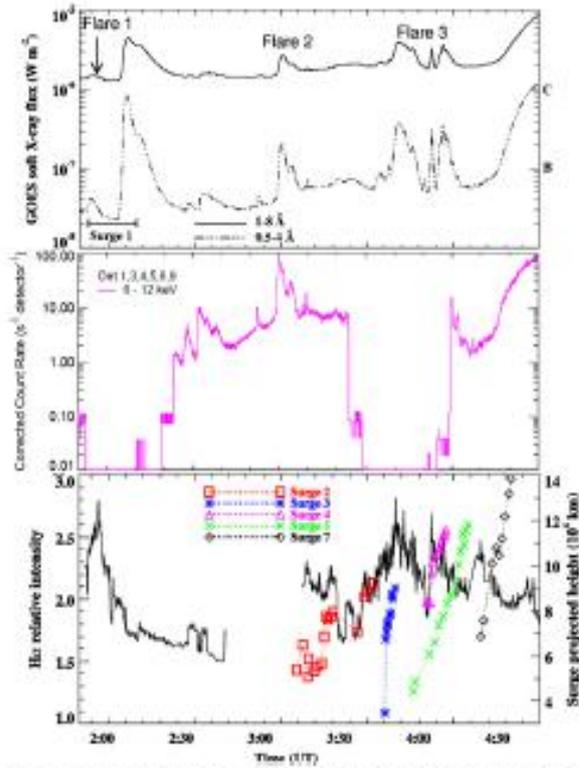


Figure 2. GOES soft X-ray flux (top panel) profiles in two different wavelengths on 2003 October 25. The $H\alpha$ relative intensity profile is well correlated with the GOES flux (bottom panel). There was a $H\alpha$ data gap in between 02:40 and 03:05 UT. There were recurrent small surges activities associated with flares at \sim 01:55 and between 03:00 UT and 04:30 UT (Flares 1, 2, and 3). The C4.3 flare during 02:02-02:12 occurred in another AR NOAA 10486 located at the eastern limb. The length-time plot of the surges is shown and demonstrates the surge-flare relationship. (A color version of this figure is available in the online journal.)

图 2. 9: 2003 年 10 月 25 日 GOES 流量 (上) 与 $H\alpha$ 相对强度。

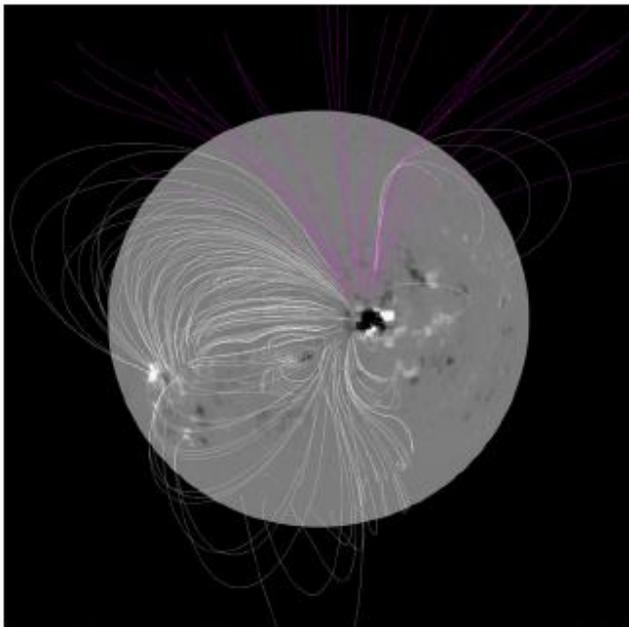


Figure 6. Potential Field Source Surface extrapolation overlotted at the *SOHO*/MDI full-disk map on 2003 October 25 on 00:04 UT, which shows the large-scale field connectivity of two active regions as well as the topology of magnetic field near the surge productivity site in AR 10484.

图 2. 10: 2003 10 月 25 日 00:04 UT 势场源表面外推 (SOHO/MDI) 显示两个活动区大规模磁场相连

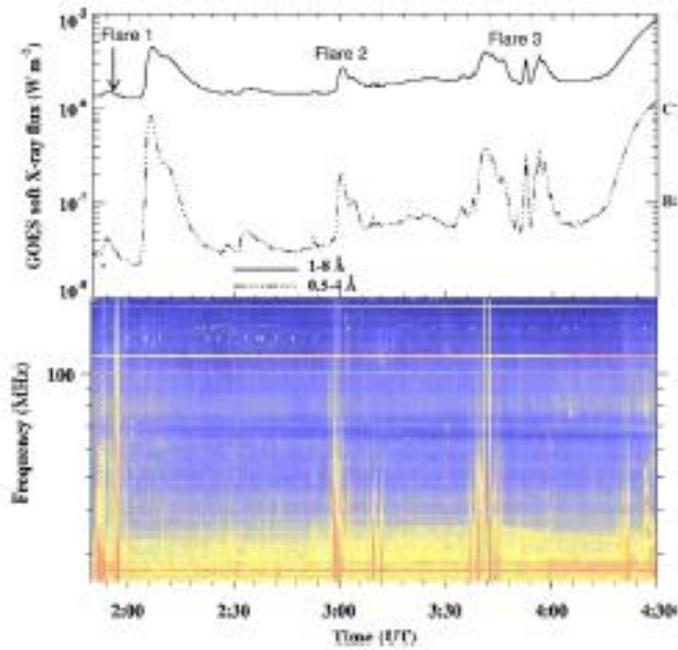


Figure 7. GOES soft X-ray light curve and Radio Type III bursts (Laurmont).
(A color version of this figure is available in the online journal.)

图 2. 11: GOES 流量与射电暴

2.2.3. 在限制耀斑中观测到的由磁重联驱动的热和非热效应

Li 等 (2005, A&A, 438, 325 - 339) 通过 RHESSI、SOHO、THEMIS、MISS (紫金山天文台近红外太阳光谱仪) 对 2003 年 10 月 20 日 1N/M1.9 限制耀斑的联合观测 (JOP157), 用磁模型计算比较了耀斑脉冲相的能量过程, NOAA 10484 活动区是一个 δ 型磁结构, 耀斑脉冲相的多重结构暗示多重磁重联过程, 两个辐射极大之间明显的结构位移说明重联过程的不同地点。利用热的及截断幂律非热分量, 可以得到高能电子幂律分布的低能截止, 另外两个模型 (热的加上厚靶及热的加上薄靶非热分量) 结构相似, 非热能量只有在第一个峰值期间贡献了约 20% 的总耀斑能量, 说明加热色球的能量主要是由热传导传输。

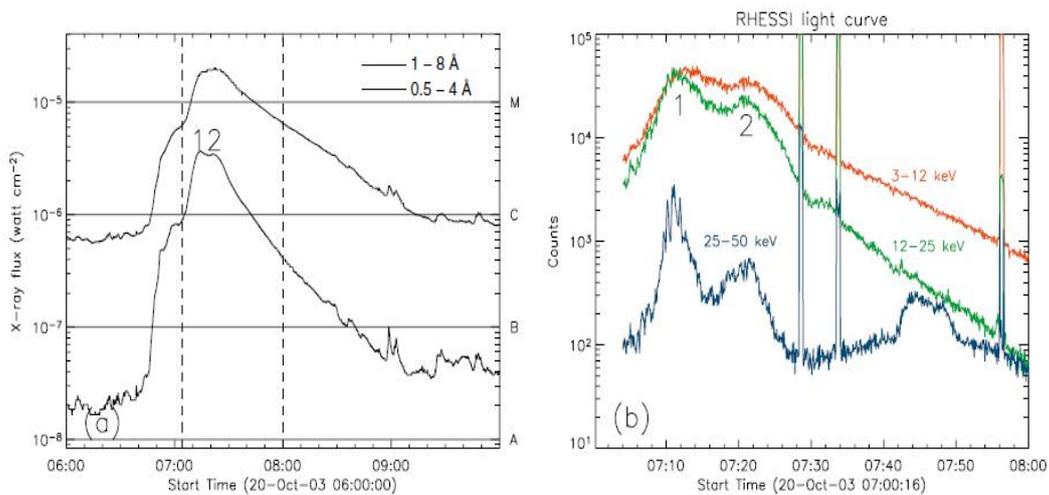


Fig. 1. a) GOES X-ray flux in 0.5–4 Å and 1–8 Å. The two dashed vertical bars indicate the start and end time of RHESSI light curves in b) and the numbers (1–2) mark the two peaks of GOES 0.5–4 Å flux in the time range of RHESSI observation. b) RHESSI light curves in the energy range of 3–12 keV, 12–25 keV, and 25–50 keV retrieved from the RHESSI data of collimators and detectors 3F–8F with a time bin of 4 s. The numbers (1–2) mark the two peaks of RHESSI light curve that temporally correspond to the two GOES 0.5–4 Å peaks marked in Frame a).

图 2. 12: GOES 流量 (左) 与 RHESSI 光变曲线 (右)

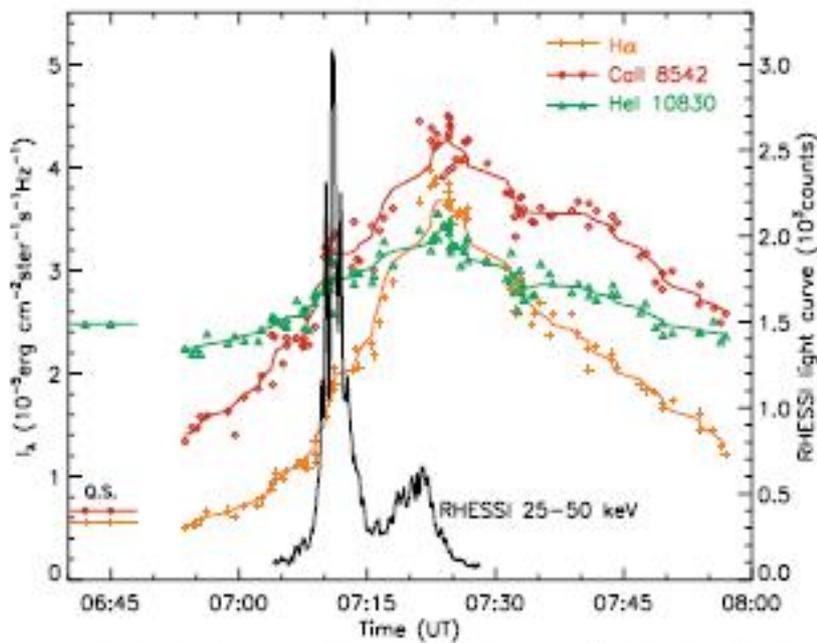


Fig. 10. Temporal evolution of the line-center intensities of H α , Ca II 8542 Å, and He I 10830 Å lines observed by MISS at PMO for the point indicated in Fig. 6c by the arrow labelled "FL". The symbols \times , \circ , Δ stand for the observed line-center intensities of H α , Ca II 8542 Å, and He I 10830 Å, respectively, and the corresponding solid lines for the smoothed ones. The horizontal short bars on the left side of the plot indicate the line-center intensities of the three lines observed in the nearby quiet-sun region (marked "QS" in Fig. 6c). Also plotted is the RHESSI 25–50 keV light curve.

图 2. 13: 紫金山天文台 MISS 观测的 H α , Ca 8542 Å 及 He 10830 Å 线中心强度时间演化

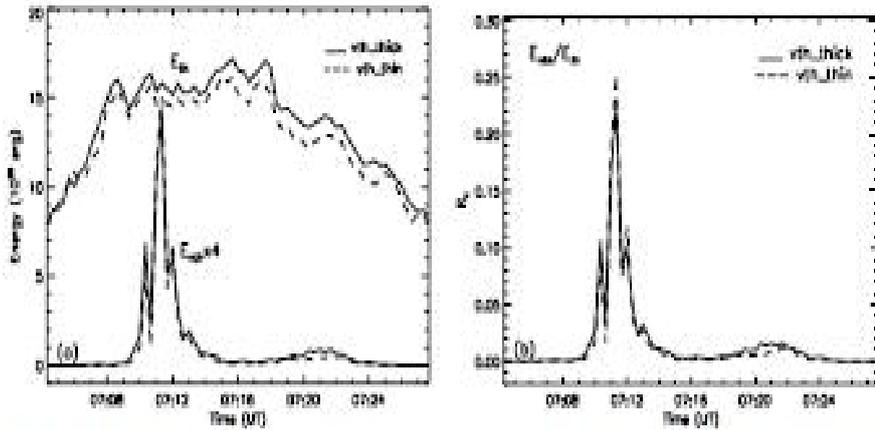


Fig. 13. a) Temporal variations of thermal energy (E_{therm} , thick line) and non-thermal energy ($E_{\text{non-therm}}$, thin line) computed from the fit parameters with the “vth+thick” (solid line) and “vth+thin” models (dashed line). b) Time profile of the ratio of non-thermal energy to thermal energy (R_{nt}) for the studied flare calculated from RHISSI spectral analysis with the “vth+thick” (solid line) and “vth+thin” (dashed line) models. The low energy cutoff for the non-thermal electron beam was set to 25 keV based on our estimation. The mean lifetime of non-thermal electrons is set to 1 s.

图 2. 14: a)热能 与非热能演化, b)非热对热能比例的时间轮廓

2.2.4. 全日面准同时磁浮现

周桂萍等 (2007, *Solar Phys*, 244, 13 – 24) 基于全球 $H\alpha$ 和 SOHO / EIT EUV 数据, 分析了 2003 年从 10 月下旬到 11 月初出现的一系列强烈的太阳爆发事件, 超过六个活动区, 包括“万圣节”事件 (NOAA10484, 10486 和 10488) 参与活动, 发现非常长的暗条通道通过六个活动区, 其中四个明显同时出现磁通量, 这意味着这些活动区之间有磁性的连接, 在三个主要活动区有相同特征性的磁云。

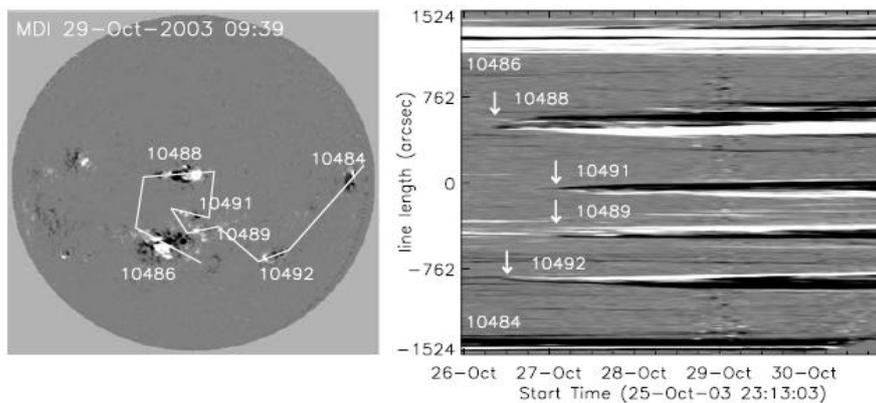


Figure 2 The time evolutions (right panel) of MDI magnetic flux density along a line across the six ARs (left panel). For the line's straight length from right, center, to the left, the positions correspond to -1524 , 0 , and 1524 arcsec, respectively, in the ordinate of the right panel. The MDI flux density evolutions along the line cover the time period from 23:13 UT on 25 October to 22:24 UT on 30 October 2003 with an interval of 96 min.

图 2. 15: 六个活动区 (左) 及沿着跨越其连接线的磁通时间演化

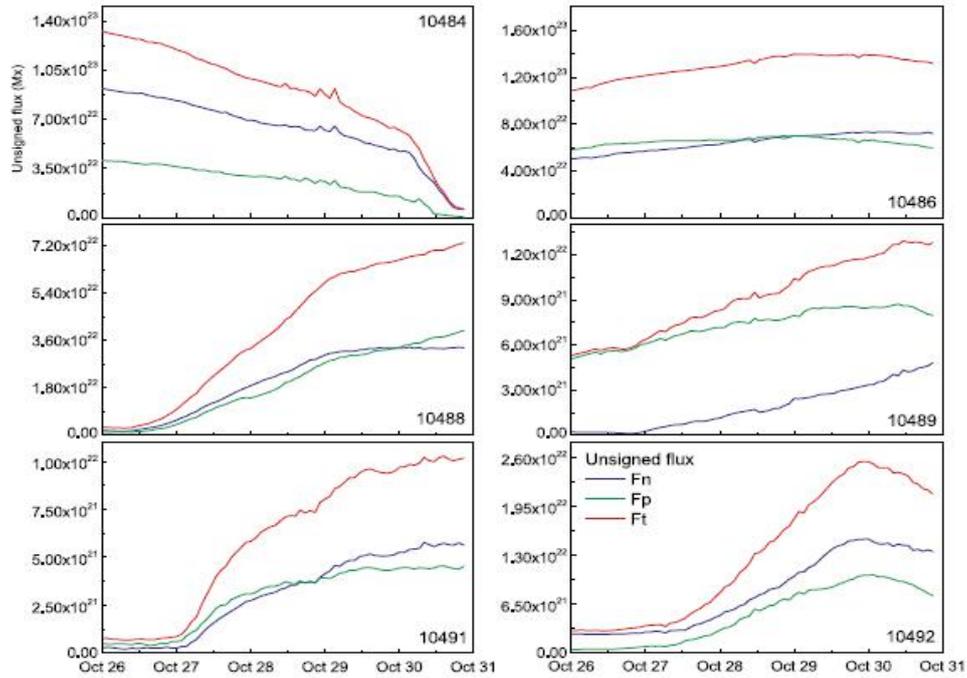


Figure 3 The unsigned emerging flux with time variations in each of the contoured ARs (indicated in Figure 1) shown with positive (F_p , green color), negative (F_n , blue color), and total ($F_t = F_p + F_n$, red color) flux from 23:59 UT on 26 October to 20:48 UT on 30 October.

图 2. 16: 磁通演化

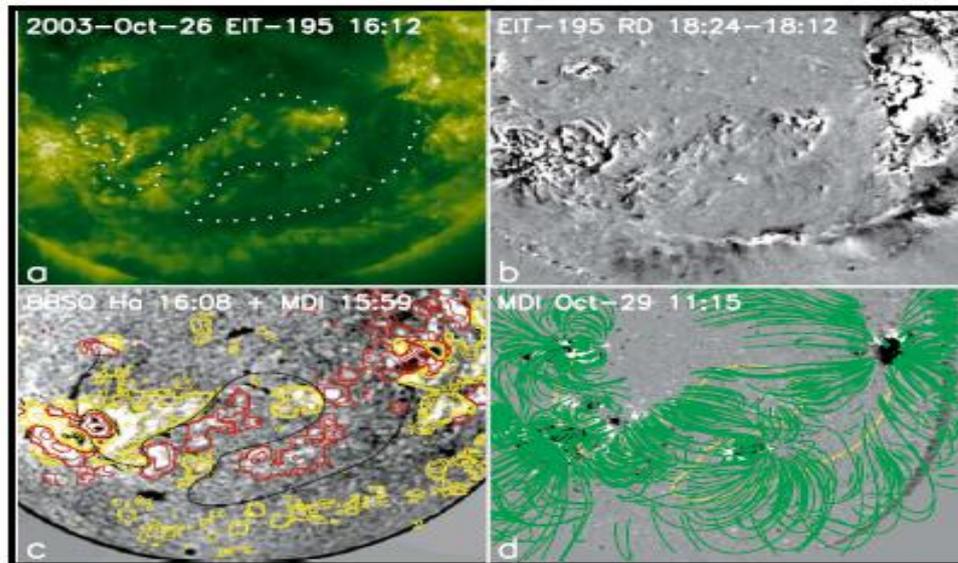


Figure 4 A long filament channel is identified and suggests a connection among the six ARs based on multi-wavelength observations. (a) An EIT 195 Å image at 16:12 UT on 26 October showing the long filament channel as a long narrow dark EUV feature (see the long dotted curve). (b) An EIT running difference (RD) image obtained by subtracting the EUV data at 18:12 from the one at 18:24 UT, which shows coronal dimming along the long filament channel accompanying the associated AR activity. The very long filament channel is situated at a long magnetic neutral line as denoted in panel (c). (c) An H α image at 15:59 on 26 October with contours of nearly simultaneous MDI data. (d) Multiple magnetic arcades overlaying the very long filament channel determined by the method of global potential extrapolation (Wang, Yan, and Wang, 2002). Its background image is an MDI magnetogram at 11:15 UT on 29 October denoting the locations of the six ARs and the long filament channel. The long yellow curve in the figure denote the long filament channel.

图 2. 17: 长暗条通道连接六个活动区。(a) EIT195Å图, (b) EIT 较差图, (c) H α 图像, (d) 与长暗条重叠的多重磁拱

2.2.5. 由具有相反磁极性及运动方向的两个小黑子的碰撞触发的连续太阳爆发

闫晓理等（2012, APJ, 143, 56）分析了在 2003 年 10 月 22 日由具有相反磁极性及运动方向的两个小黑子的碰撞触发的伴随 CME 事件的连续 M 级太阳耀斑爆发，从 TRACE 白光像及 SOHO/MDI 磁图中观测该活动区的演化看，一个大黑子和一个具有相反极性的小黑子在 10 月 21 日 15:00 UT 到 10 月 23 日 16:24 UT 期间从东北向东南顺时针旋转分别 33 度和 18 度。在它们运动过程中，负极性的小黑子与正极性及反向运动的小黑子发生碰撞，在此次碰撞过程中，该活动区产生了两个连续 M 级耀斑（GOES）及 CME 事件（LASCO）。通过分析两个小黑子在极性翻转线（PIL）的磁场发现，在两个 M 级耀斑开始附近突然出现了挤压，之后又恢复。它们排除了在 PIL 附近磁场浮现的可能。从两 M 级耀斑的 TRACE 1600 Å 亮斑和 RHESSI 硬 X 射线源，发现两耀斑的位置处在 PIL 上几乎相同的位置。

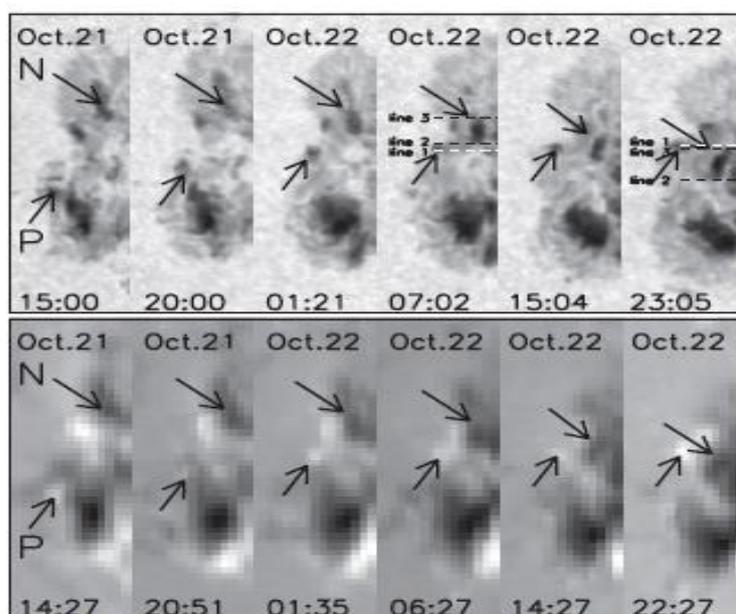


Figure 2. Upper panel shows the motions of the two small sunspots with opposite polarities and motional directions in TRACE WL. The lower panel shows the evolution of the two sunspots seen from 96 minute magnetograms. The arrows denote the positions of the two sunspots with time. "P" and "N" have the same meanings as in Figure 1. The three dashed lines in the upper panel are used to define the start and the end of the collision. Line 1 is parallel to the equator and crosses the center of the positive sunspot. Lines 2 and 3 are also parallel to the equator and denote the south forefront and the north back end of the small sunspot with negative polarity.

图 2. 18: 由 TRACE 白光像（上）及 MDI 磁图（下）观测到的两小黑子运动

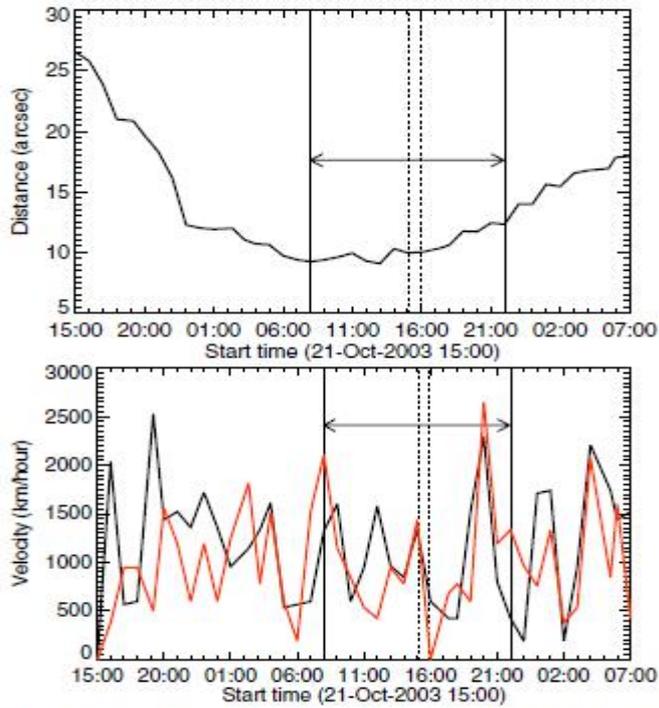


Figure 3. Upper panel: the change of the distance between the geometric center of the small sunspot with positive polarity and the south forefront of the small sunspots with negative polarity. Lower panel: the speed of the two sunspots (black line: the sunspot with positive polarity; red line: the sunspot with negative polarity). The two vertical dashed lines denote the onset times of the two M-class flares. The two vertical solid lines indicate the start and end of the collision marked by the double arrows.

图 2. 19: 两黑子之间的距离 (上) 及其运动速度演化 (下)

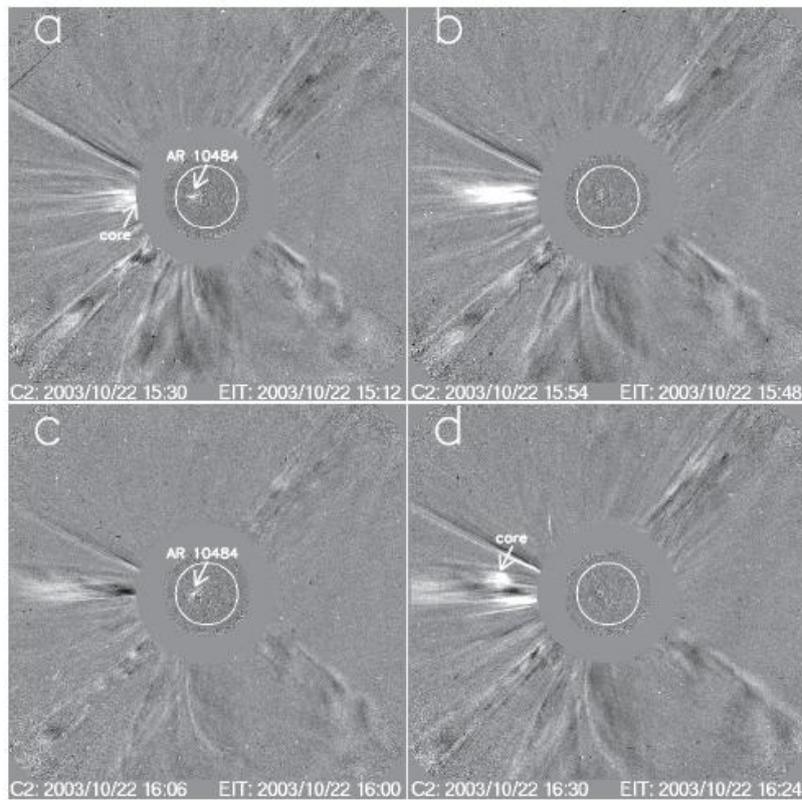


Figure 8. SOHO/LASCO difference images with superposed EIT difference images. The arrows denote the position of NOAA AR 10484 and the cores of CMEs.

图 2. 20: SOHO/LASCO 差分图叠加 EIT 差分图

2.2.6. 秃斑拓扑中的爆炸喷流和脉冲爆发耀斑

一些宽喷流与耀斑相伴，另一些与喷流状 CME 相伴，爆炸喷流(blowout jet)是宽极紫外和 X 射线喷流 (Jet) 的一个子类，它们可能是标准准直喷流和 CME 的联系。Chandra 等(2017, A&A, 598, A41)通过分析 2003 年 10 月 21-24 日 10484 活动区一系列复发宽喷流，一个与 10 月 23 日 02:41 UT 的 M2.4 耀斑同时发生，两事件都被 ARIES H α 太阳塔望远镜、TRACE、SOHO 及 RHESSI 观测到，耀斑是尖端脉冲并尾随窄 CME。通过无力场模型拓扑分析发现秃斑(BP)在耀斑地点，BP 拓扑在耀斑前存在了至少两天。与 BP 相关的大规模场线代表了开放环，证实与全局无源势表面模型。特征显示观测到的宽喷流似乎是爆炸类，磁重联可能发生在由通量绳的连续变形导致的 BP 分割线上，重联过程可能导致冷通量绳物质向重联的开放磁力线移动从而驱动一系列复发的爆发喷流及伴随 CME。

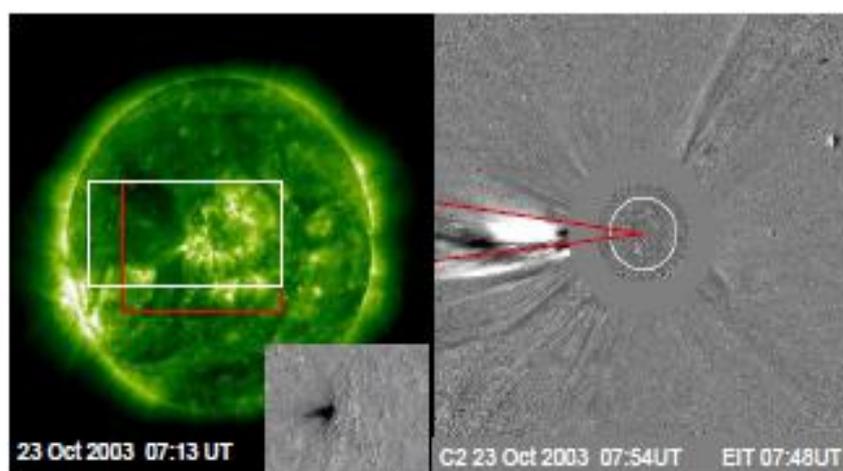


Fig. 1. EIT image and LASCO C2 difference image of a jet and associated narrow CME. *Left panel:* full-disk EIT image on 23 October 2003 at 07:13 UT showing a broad jet originating from the eastern border of AR 10484 at its maximum extension. The inset in its bottom right is the partial EIT difference image within the red rectangle in the full-disk image. *Right panel:* LASCO C2 difference image of the associated narrow CME. The two red continuous lines are drawn to indicate the CME angular width. A very weak feature is found to the north of the CME bulk emission. This feature could be attributed to a projection effect because the CME propagation direction has an important component toward the observer, as deduced from the source region location. If we take this as the northern CME edge, then the AW would be of $\sim 23^\circ$, while the true width of the ejection is smaller. The broad feature to the south corresponds to a previous CME. The coronal evolution in the region indicated by the white rectangle is available as a movie. These white and red rectangles partially overlap to the north and west.

图 2. 21: EIT 图与 LASCO C2 差分图显示与窄 CME 联系的喷流

表 2.2: NOAA10484 活动区复发喷流

Table 1. Recurrent jets in AR 10484.

21 October 2003		
Start time (UT)	Max. length (Mm)	LASCO C2 feature
14:24:10	44	*Faint narrow CME (AW < 10) in PA = 105, 14:54 UT
15:12:11	55	[†] Narrow CME (AW = 18) in PA = 98, 16:06 UT
17:48:12	48	Corona contaminated by CME from AR10486
22 October 2003		
Start time (UT)	Max. length (Mm)	LASCO C2 feature
00:48:11	59	Corona contaminated by CME from AR10486 at 00:54 UT
02:36:11	168	Corona contaminated by CME from AR10486 at 03:54 UT
05:24:11	59	Corona contaminated by previous CME
09:48:11	217	Jet-like CME (AW < 5) in PA = 80, 10:30 UT
11:00:11	180	*Faint narrow CME (AW = 10) in PA = 90, 11:54 UT
14:24:11	61	Not evident, likely because faint, narrow, and high angle
15:12:11	190	^{††} Narrow CME (AW = 15) in PA = 90, 15:30 UT
16:00:10	137	[†] Narrow CME (AW = 20) in PA = 85, 16:30 UT
23 October 2003		
Start time (UT)	Max. length (Mm)	LASCO C2 feature
01:25:55	121	*Faint jet-like CME (AW < 10) in PA = 92, 2:06 UT
02:36:11	217	^{††} Narrow CME (AW = 20) in PA = 90, 3:06 UT
06:36:11	82	[†] Narrow CME (AW = 15) in PA = 90, 7:31 UT
10:14:14	167	Jet-like CME (AW = 10) in PA = 80, 11:30 UT
11:48:11	243	Not distinguishable from previous jet, likely high angle
14:25:56	64	Not distinguishable from pre-existing structures, high angle
18:00:11	130	Not distinguishable from pre-existing structures, high angle
20:12:11	58	Corona contaminated by CME from AR10486 at 20:06 UT
22:00:11	166	Corona contaminated by CME from east limb, north of AR10486
23:12:11	76	Narrow CME (AW < 5) in PA = 78, 00:06 UT
24 October 2003		
Start time (UT)	Max. length (Mm)	LASCO C2 feature
00:24:11	89	Not distinguishable from pre-existing structures, high angle
06:00:11	91	Not distinguishable from pre-existing structures, high angle
08:24:11	150	*Narrow CME (AW = 10) in PA = 102, 08:54 UT
09:48:11	149	Faint CME (AW = 27) in PA = 260, 11:06 UT, high angle
20:24:11	47	Jet-like CME (AW < 5) in PA = 67, 21:30 UT
21:36:11	141	Jet-like CME (AW < 10) in PA = 68, 22:30 UT
22:36:11	191	Jet-like CME (AW < 5) in PA = 70, 23:30 UT

Notes. An * in the third column indicates that the association with the corresponding jet is marginal. A superscript “†” and “††” indicates that the coronal counterpart was reported to the CDAW SOHO/LASCO and the CACTus CME catalogs, respectively. The words “high angle” indicate a large angle between the observed structure and the POS. The hours indicate the first time of appearance in LASCO C2 field of view (FOV). The angular width (AW) and the position angle (PA) are expressed in degrees with the PA measured counter-clockwise from solar north.

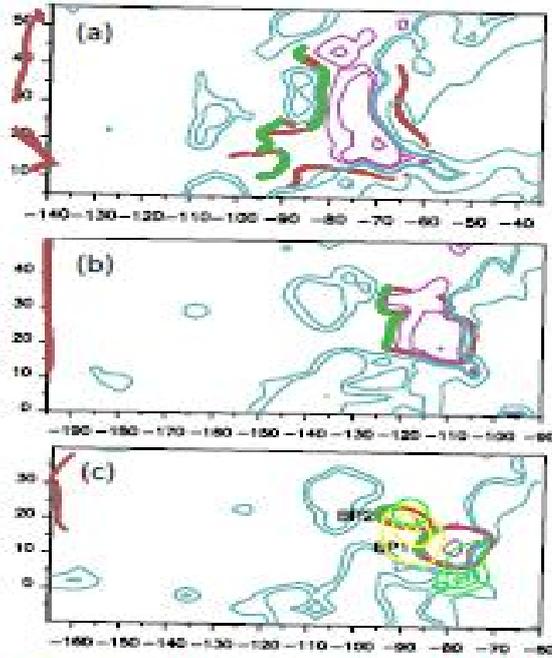


Fig. 10. Magnetic field models showing the location of the BPs and the intersections with the photosphere of their associated separatrices from 21 to 23 October 2003. **a)** Corresponds the MIDI map at 20:47 UT on 21 October, **b)** to the MIDI map at 14:23 UT on 22 October, and **c)** to that at 01:35 UT on 23 October. The latter is the closest in time to the events we analyze in detail in this article. In panel **c)** we labeled the BPs as BP1 and BP2 and overlaid the RHESSI contours shown in Fig. 4d (light green and yellow contours correspond to the 50–100 keV range and 10–15 keV range, respectively). The *above* panels are shown from the point of view of the observer. The inclination of the sides of the boxes (defined in the local frame) indicates that the AR was not at CML. BPs are shown as the thickest green continuous lines, while the magenta thick continuous lines correspond to the photospheric trace of the BP separatrices. The contours correspond to ± 50 G, ± 100 G, and ± 500 G (magenta (cyan) for positive (negative) field values) and the axes are in Mm.

图 2. 22： 磁力线模型显示 BP 位置及与分界线在光球处交叉面

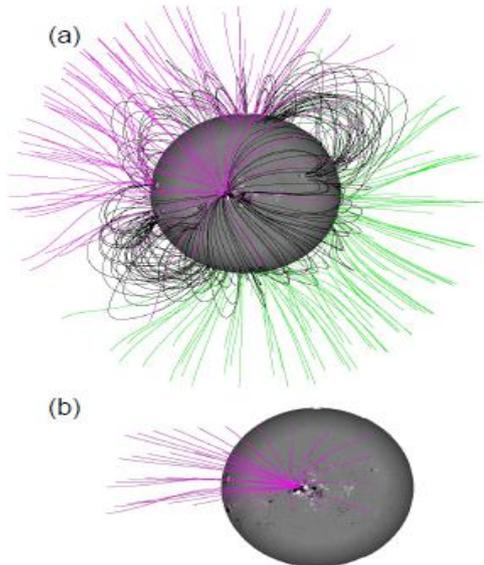


Fig. 13. PFSS model of CR 2009 with AR 10484 at CMP (Carrington longitude 5.5°). **a)** This drawing depicts the global coronal field. **b)** This drawing depicts the selection of field lines chosen in a box of $20 \times 20^\circ$ with the AR in its center. The field-line color convention is such that black indicates closed lines and pink (green) corresponds to open lines anchored in the negative-polarity (positive-polarity) field.

图 2. 23： NOAA10484 活动区势场外推

2.2.7. NOAA10484, 10486 和 10488 活动区的色球物质运动和光球黑子旋转

Hardersen 等(2013, APJ, 773, 60)利用改进的太阳光学网络连续谱(630.2 nm)和 $H\alpha$ (656.2 nm) 数据: (1) 检测和测量在光球和色球中发生的固有太阳黑子旋转, (2) 识别和测量色球暗条质量运动, 和 (3) 评估任何大规模的光球和色球质量耦合, 发现在 10 月 29 日 AR 10486 的两个大太阳黑子之间的存在显著的反向旋转, 10 月 27 日 NOAA AR 10484 的离散暗条质量运动, 至少与一个 C 级太阳耀斑相关联。

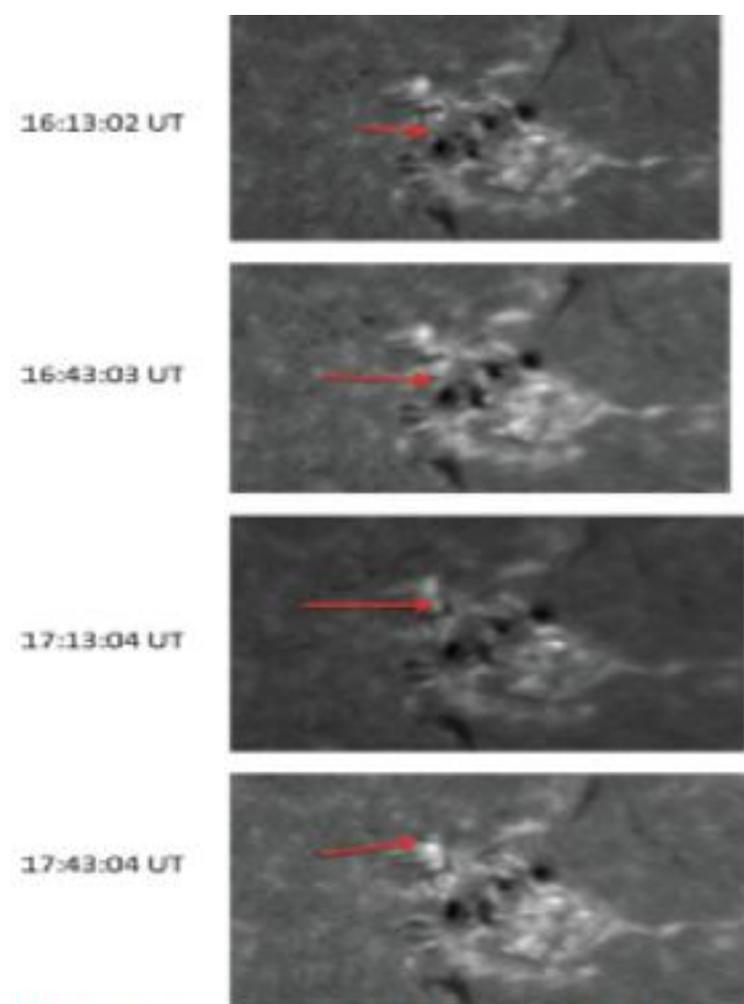


Figure 4. Time sequence of four $H\alpha$ images of NOAA AR 10484 on 2003 October 27, from 16:13 UT to 17:43 UT. Discrete filament mass can be seen migrating north in a reverse sigmoid fashion, beginning with the top image and moving downward. Additional mass movement at $\sim 17:30$ UT directly precedes a C9.0 class flare that begins at $\sim 17:44$ UT.

(An animation of this figure is available in the online journal.)

图 2. 24: NOAA 10484 活动区在 2003 年 10 月 27 日 16:13UT 至 17:43UT 四个 $H\alpha$ 图序列, 显示分立的暗条按反 S 型朝北迁移

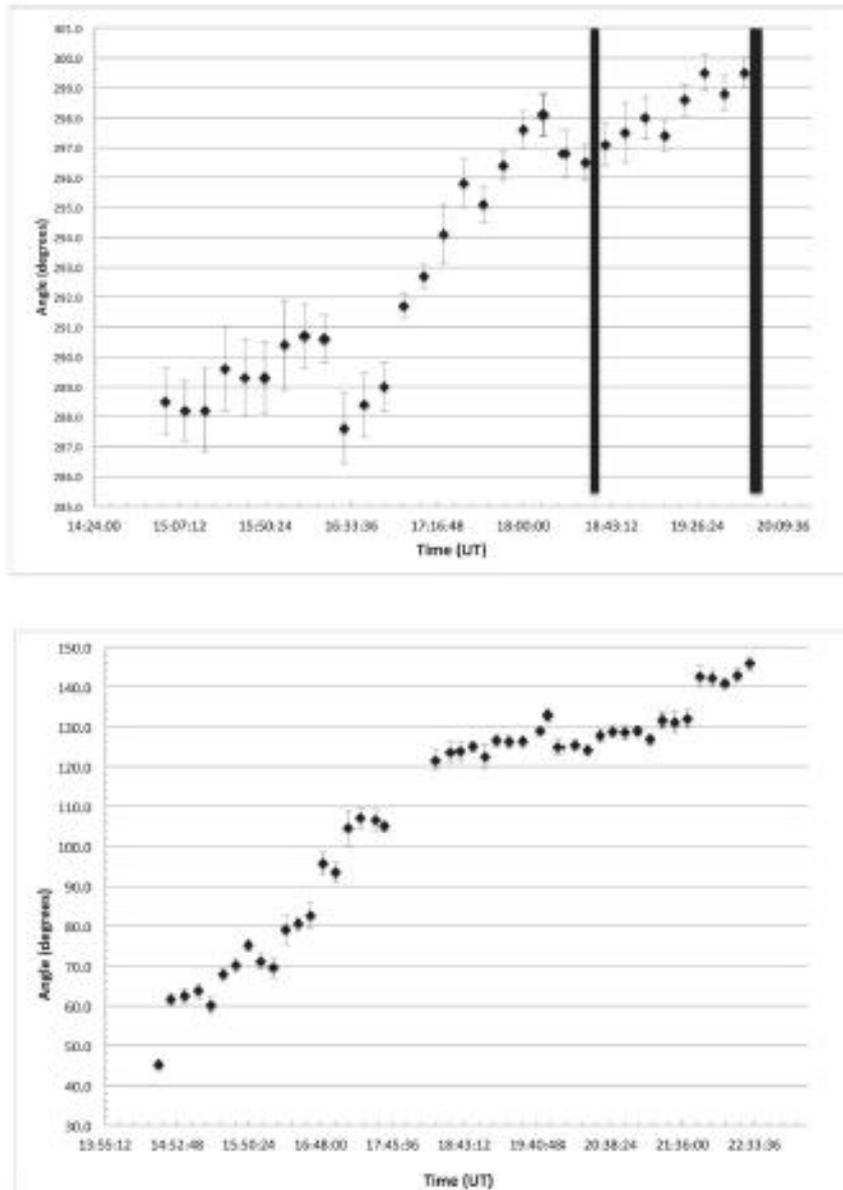


Figure 5. Rotational motion of filaments as measured from time slices of the following sunspot in NOAA AR 10484 on 2003 October 27, top, and on October 28, bottom. The motion on 2003 October 27 corresponds with filament mass motion moving to the north/northeast of the following sunspot that is time coincident with a C9.0-class solar flare. Vertical bars in the top figure represent the approximate times of the C7.5 and C9.0 flares, respectively.

图 2. 25: 从 NOAA 10484 活动区在 2003 年 10 月 27 日 (上) 及 28 日 (下) 测量的暗条旋转运动。10 月 27 日运动对应于在时间上与 C9.0 耀斑一致的暗条质量的朝 (东) 北运动的暗条质量的运动

2.3. 主要科学贡献

NOAA 10484 活动区是“万圣节”事件中不是很活跃，NOAA10484 耀斑是一个限制耀斑，并没有形成大的爆发现象，相关内容主要是围绕与 NOAA 10486 和 10488 活动区的联合研究。

● 物理现象及参量研究

➤ 与 NOAA10484 活动区相关的多重波浪观测

利用 $H\alpha$, UV 及射电观测, 对 2003 年 10 月 25 日 NOAA10484 活动区进行了复发冲浪 (surge) 多波段分析, 在每个 surge 底部都发现了与子耀斑相关的几个两结构, 并触发了 III 型射电暴, 大 surge 由形成扇形区域的几束喷流组成, SOHO/MDI 观测显示 surge 前几天 (18-20 日) 在活动区东侧浮现大的二级子。

➤ 秃斑拓扑中的爆炸喷流和脉冲爆发耀斑

一些宽喷流与耀斑相伴, 另一些与喷流状 CME 相伴, 爆炸喷流 (blowout jet) 是宽极紫外和 X 射线喷流 (Jet) 的一个子类, 它们可能是标准准直喷流和 CME 的联系。通过分析 2003 年 10 月 21-24 日 10484 活动区一系列复发宽喷流, 一个与 10 月 23 日 02:41 UT 的 M2.4 耀斑同时发生, 耀斑是尖端脉冲并尾随窄 CME。通过无力场模型拓扑分析发现秃斑 (BP) 在耀斑地点, BP 拓扑在耀斑前存在了至少两天。与 BP 相关的大规模场线代表了开放环, 证实与全局无源势表面模型。特征显示观测到的宽喷流似乎是爆炸类, 磁重联可能发生在由通量绳的连续变形导致的 BP 分割线上, 重联过程可能导致冷通量绳物质向重联的开放磁力线移动从而驱动一系列复发的爆发喷流及伴随 CME。

● 运动与机制研究

➤ 在限制耀斑中观测到的由磁重联驱动的热和非热效应

耀斑脉冲相的多重结构暗示多重磁重联过程, 两个辐射极大之间明显的结构位移说明重联过程的不同地点。利用热的及破碎幂律非热分量, 可以得到高能电子幂律分布的低能截止, 另外两个模型 (热的加上厚靶及热的加上薄靶非热分量) 结构相似, 非热能量只有在第一个峰值期间贡献了约 20% 的总耀斑能量, 说明加热色球的能量主要是由热传导传输。

➤ 由具有相反磁极性及运动方向的两个小黑子的碰撞触发的连续太阳爆发

分析了在 2003 年 10 月 22 日由具有相反磁极性及运动方向的两个小黑子的碰撞触发的伴随 CME 事件的连续 M 级太阳耀斑爆发, 一个大黑子和一个具有相

反极性的小黑子在 10 月 21 日 15:00 UT 到 10 月 23 日 16:24 UT 期间从东北向东南顺时针旋转分别 33 度和 18 度。在它们运动过程中，负极性的小黑子与正极性及反向运动的小黑子发生碰撞，在此次碰撞过程中，该活动区产生了两个连续 M 级耀斑（GOES）及 CME 事件（LASCO）。通过分析两个小黑子在极性翻转线（PIL）的磁场发现，在两个 M 级耀斑开始附近突然出现了挤压，之后又恢复。从两 M 级耀斑的 TRACE 1600 Å 亮斑和 RHESSI 硬 X 射线源，发现两耀斑的位置处在 PIL 上几乎相同的位置。

● “万圣节”事件联合研究

➤ 怀柔站观测到的三个超级活动区

怀柔观测站的多通道太阳望远镜观测到的三个超级活动区（NOAA 10484, 10486 和 10488），强剪切与快速磁通浮现可能是这些事件的主要起因。

➤ 全日面准同时磁浮现

2003 年从 10 月下旬到 11 月初出现的一系列强烈的太阳爆发事件中，超过六个活动区，包括“万圣节”事件（NOAA10484, 10486 和 10488）参与活动，发现非常长的暗条通道通过六个活动区，其中四个明显同时出现磁通量，这意味着这些活动区之间有磁性的连接，在三个主要活动区有相同手征性的磁云。

➤ NOAA10484, 10486 和 10488 活动区的色球物质运动和光球黑子旋转

发现在 10 月 29 日 AR 10486 的两个大太阳黑子之间的存在显著的反向旋转，10 月 27 日 NOAA AR 10484 的离散暗条质量运动，至少与一个 C 级太阳耀斑相关联。

2.4. 其他

参见第三、四章关于 NOAA10486 及 10488 活动区情况。

参见第三章 3.4.3.4.2 观测影像资料, p. 118

参见第六章 6.2.6.2.21 两个活动区在光球及光球下的水平流动, p.错误! 未定义书签。

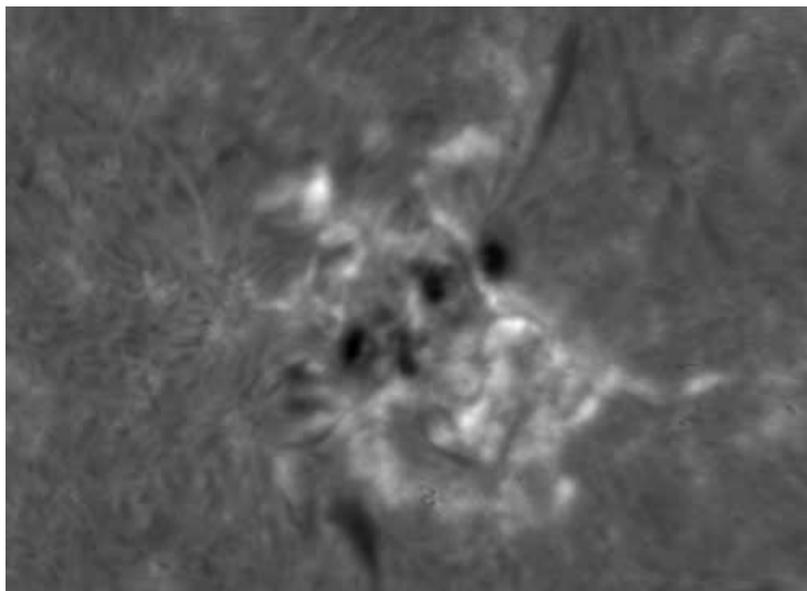


图2. 26: NOAA 10484 活动区在2003年10月27日 16:13UT至 17:43UT 影像([Hardersen, 2013, APJ, 773, 60](#))

2.5. 主要参考文献

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第三章 NOAA10486 活动区（万圣节）事件

3.1. 事件概述

NOAA 10486 活动区是在 2003 年 10 月 23 日出现在日面东边缘（S16E81）的活动区，于 11 月 5 日消失在日面西边缘（S17W89）。在 10 月 23 日时的磁位型为 Alpha，坐标为 S16E81，面积为 150，到第二天（10 月 24 日）就已经演化为 Beta-Gamma-Delta 型，坐标为 S16E70，面积增加到 1160；到 11 月 5 日当该活动区即将从西边缘消失时，坐标为 S17W89，面积为 630，磁位型仍然为复杂的 Beta-Gamma-Delta 型。该活动区是“万圣节”事件中最活跃的活动区，产生了 9 个 X 级耀斑，其中包括 1 个 X28+，2 个 X17、1 个 X10，以及大量的 M 级以上耀斑。该活动区还产生了 12 个大型 CME 事件，最高速度超过了 2000 km/s，其中 10 月 28 日的 CME 对地效应非常显著，11 月 4 日的 CME 是“万圣节”事件中最强的高能事件。

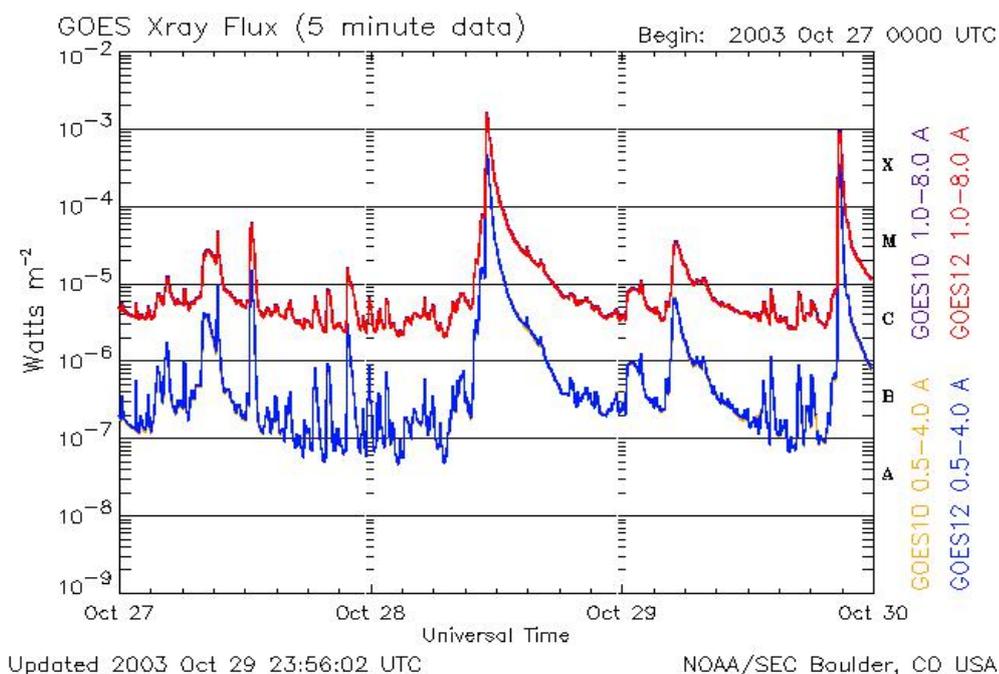


图 3.1: GOES X 射线流量图（2003 年 10 月 27-30 日）

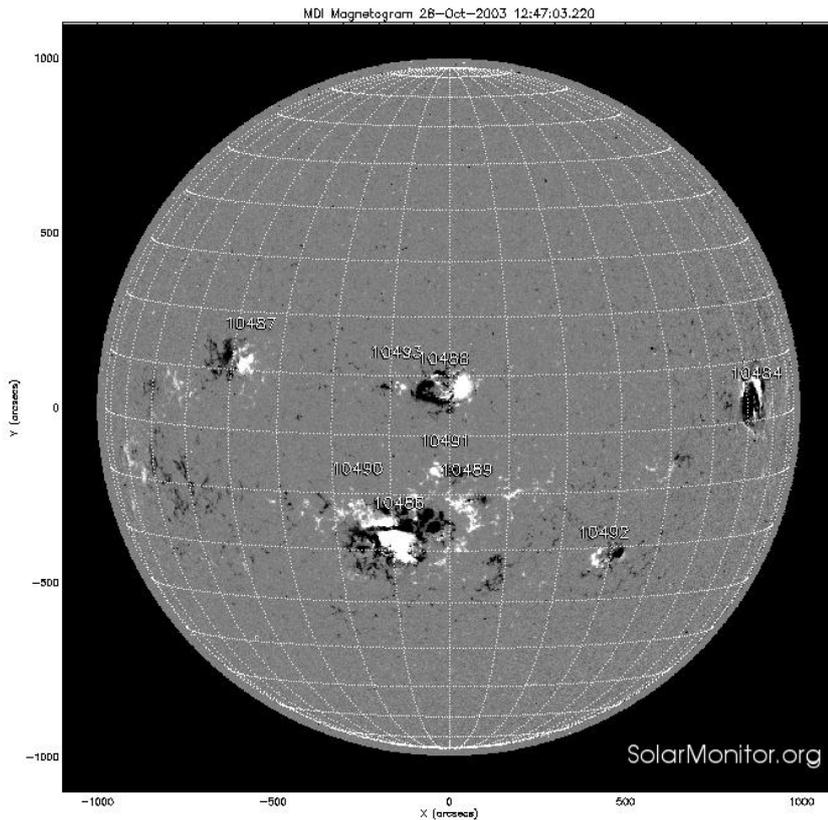


图 3. 2: NOAA10486 活动区全日面磁图(2003 年 10 月 28 日)

3.1.1. 事件特征

- 事件观测时间: NOAA 10486 活动区于 2003 年 10 月 23 日出现在日面东边缘, 11 月 5 日消失在日面西边缘。
- 最大面积: 2200 日面单位; 位置: S15E45; 时间: 10 月 26 日
- 磁位型: $\beta\gamma\delta$
- X 级耀斑数量: 9 (其中包括 1 个 X28 级, 2 个 X17 级、1 个 X10 级)
- M 级耀斑数量: 23
- 最大耀斑: X28 级; 时间: 2003 年 11 月 4 日 19: 57UT; 位置: S19W83
- 高能事件: 11 月 4 日的 CME 是“万圣节”事件中最强的高能事件, 由于此时 10486 已经到达日面西边缘, 幸而未有导致严重的对地效应。
- CME 事件: 12 个大型 CME 事件, 其中发生在 10 月 28 日、29 日和 11 月 4 日的三个 CME 的速度都超过了 2000 km/s, 分别与 X17 级、X10 级和 X28 级耀斑相关。

- 对地效应：电离层扰动，10月28日的 CME 对地效应非常显著，10月29-30日地磁暴达到了 $Dst=-350$ ， $Kp=8$ 。

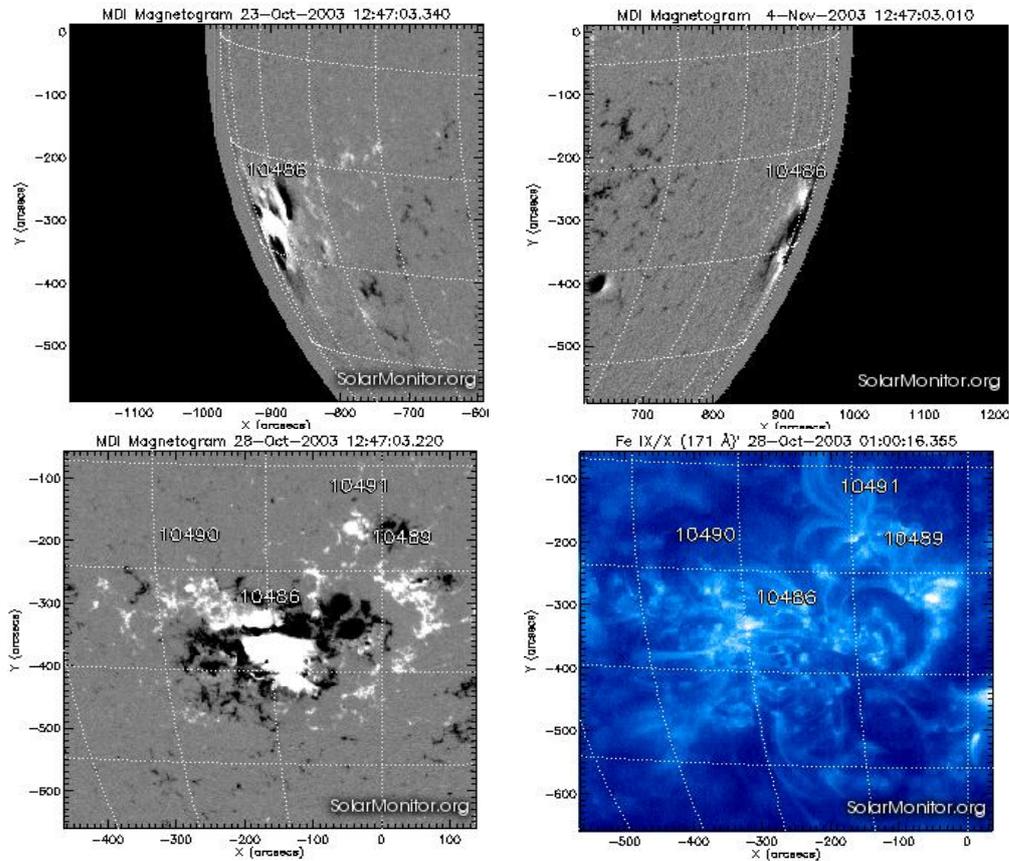


图 3.3：黑子图与 EUV 观测

3.1.2. 观测特征

该活动区产生了 9 个 X 级耀斑（其中包括 1 个 X28+）以及大量的 M 级以上耀斑，还产生了 12 个大型 CME 事件。在 2003 年 10 月 28 日，活动区 10486 位于 S16E18，面积达到 2180，磁位型为 $\beta\gamma\delta$ 。在 UT 11:12，该活动区产生了一个 X17.2 级双带耀斑，伴随暗条爆发及快速日冕物质抛射，最高速度超过了 2000 km/s，该 CME 在行星际空间用了不到 20 个小时（12:42）就到达了地球，导致 SOHO/LASCO/C3 的饱和而产生雪花效应，产生的地磁扰动造成人造卫星的损坏、飞机航班路线的变更、瑞典境内的电力供应中断、长距离无线电通讯的失灵以及远达佛罗里达州的极光。10月28日的 CME 对地效应非常显著，11月4日的 CME 是“万圣节”事件中最强的高能事件，产生了 II、III 和 IV 型射电暴。

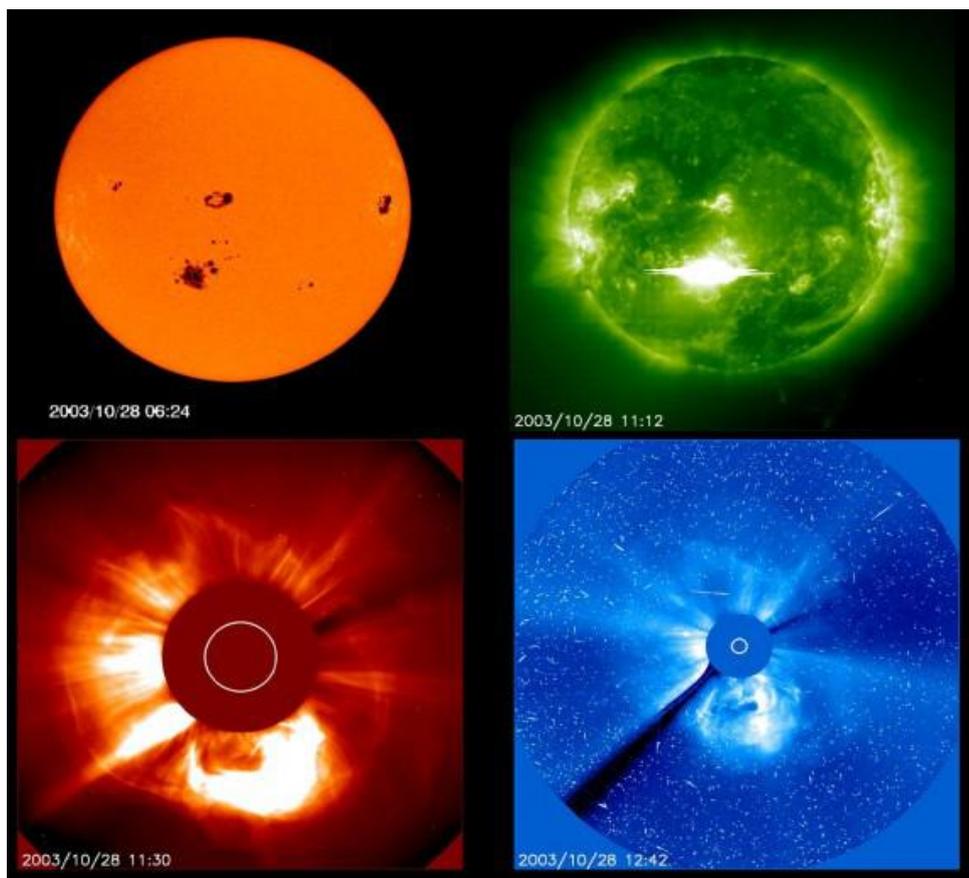


图 3.4: 活动区特征与 CME

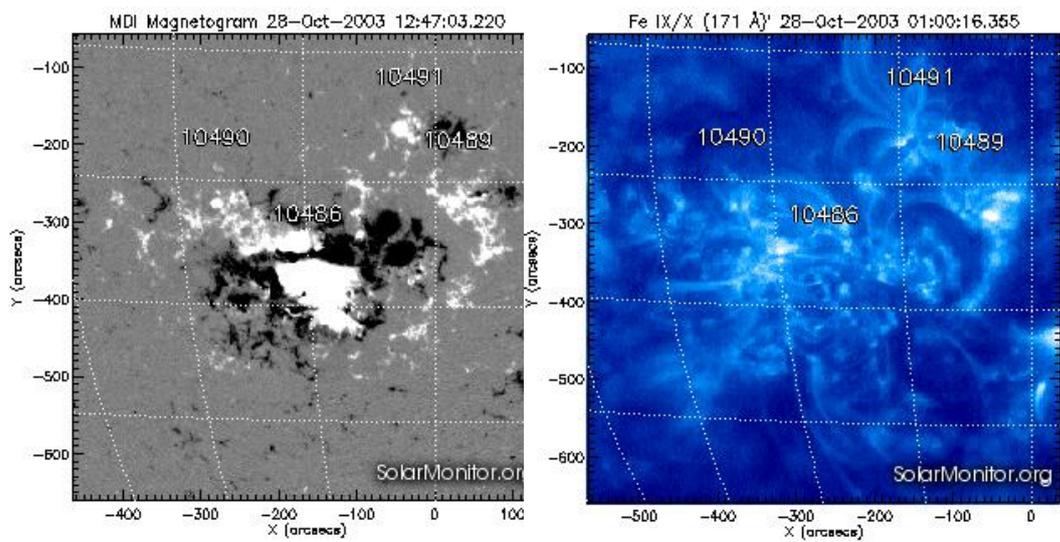


图 3.5: 黑子磁图与 172 埃观测

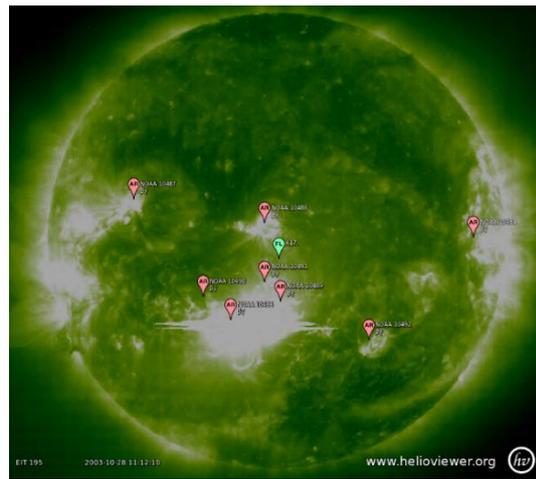
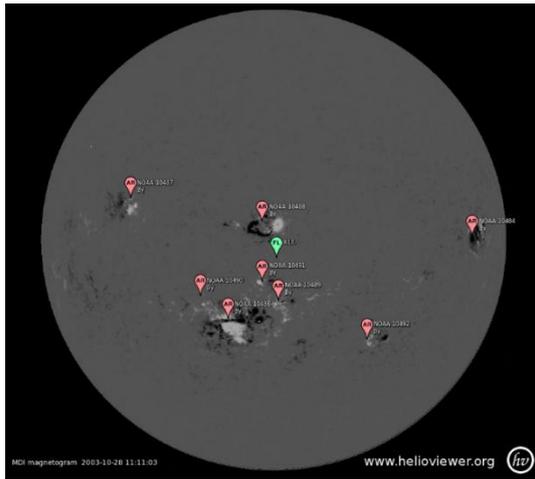


图 3. 6: 2003 年 10 月 28 日 X17 级耀斑

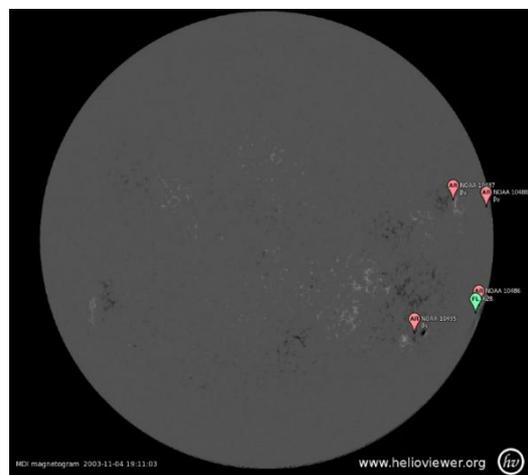
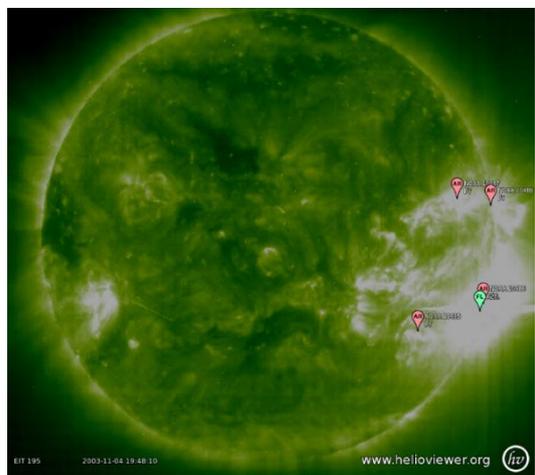


图 3. 7: 2003 年 11 月 4 日 X28 级耀斑

- “万圣节”事件由三个活动区 NOAA 10484、10486 和 10488 的相关活动组成，其中以 10486 产生的耀斑、CME 和地磁暴最多，以及 II、III 和 IV 型射电暴。
- 10486 活动区产生了 X28 的大耀斑，是“万圣节”系列事件中最为活跃的活动区，国内外研究人员对该活动区进行了多方位的研究，使用的数据包括多波段的成像以及流量数据，包括磁场、极紫外、白光、近红外及射电等，研究了该活动区的磁能变化，产生的耀斑及 CME，以及相关爆发活动的行星际、对地效应。

3.2. 相关事件案例研究

NOAA 10486 活动区是“万圣节”事件最为活跃的活动区，产生了 9 个 X 级耀斑，其中包括有史以来最强的耀斑 (X28+)，还产生了 12 个大型 CME 事件，产生的地磁扰动导致了人造卫星的损坏、长距离无线电通讯的失灵以及远达佛罗里达州的北极光。因此，与该事件相关的研究范围包括从日面光球层、过渡区、日冕层、行星际空间到近地空间的各个领域。与该事件有关的研究论文不少于 100 篇，我们从中选择了部分文献，特别是太阳物理方面的，加以综述。

3.2.1. 超级活动区 NOAA10486 流场的多波段研究

Deng (2006, APJ, 644, 1278 - 1291) 使用 National Solar Observatory/Sacramento Peak (NSO/SP)G 段 (GB)、白光(WL)和近红外(NIR)数据及 SOHO/MDI 数据，运用局部相关跟踪方法，分析了 NOAA10486 活动区的水平活动场，在 X10 耀斑出现前，沿磁中性线观测到了长时间持续水平及垂直剪切流动，流动方向没有变为指向更高的光球，在剪切运动区域流动速度减弱，而在没有剪切运动的区域，流动速度随高度增加。在 X10 耀斑之后，磁场梯度增加了，而在中性线附近，水平及垂直剪切流动大大提高了。这意味着，在耀斑之后，在中性线附近的光球剪切流动及局部磁场剪切可能会增加，正说明剪切或缠绕带的能量释放。

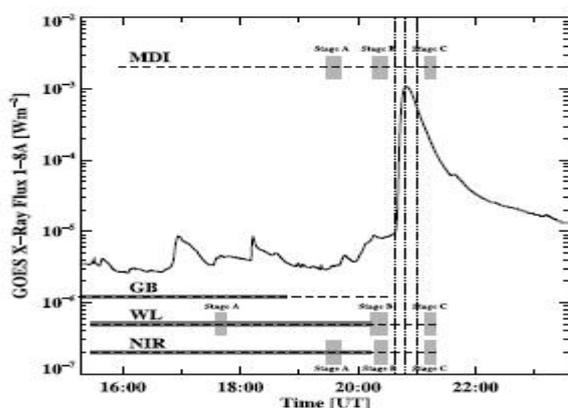


FIG. 2.—GOES soft X-ray flux in the range 1–8 Å on 2003 October 29. The X10 flare started at 20:37 UT, peaked at 20:49 UT, and ended at 21:01 UT, as indicated by the three vertical dotted lines. The horizontal dashed lines indicate the duration of the data sets. There are some data gaps during these time intervals. The horizontal solid lines superposed on each dashed line represent the time range over which the flow fields are averaged for aspect 1. The widths of the vertical gray bars indicate the time stages over which the data are averaged for aspect 2.

图 3. 8: 2003 年 10 月 29 日 GOES21:01UT 软 X 射线流量

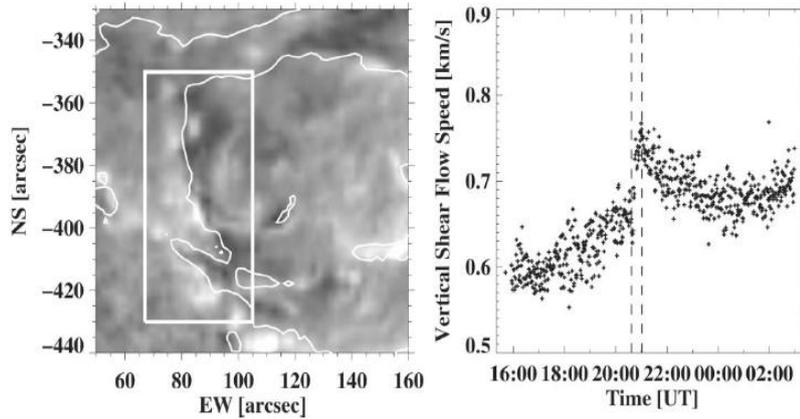


FIG. 9.—Left: MDI Dopplergram at 19:12 UT on 2003 October 29 superposed with the magnetic neutral line. Right: Evolution of the vertical shear flow speed calculated in the box region of the left panel. The two vertical dashed lines mark the beginning and end of the X10 flare.

图 3. 9: MDI 磁图 (左) 与垂直剪切流速的演化, 两虚线表示 X10 耀斑发生期间

3.2.2. 太阳耀斑的震动辐射

Donea 和 Lindsey (2005, APJ, 630:1168 - 1183) 利用 GOES、MDI、RHESSI、TRACE、GONG 及位于夏威夷 Haleakala 的 Mees 太阳观测站的矢量成像磁图 (IVM), 分析了 2003 年 10 月 28-29 日 NOAA10486 活动区的震动波, 用日震图像方法来看波的震动源, 钠 D1 发射线 (k6768) 观测显示在耀斑起始存在向下传播的激波/凝结现象, 多数耀斑并不是声学活跃的, 由高能粒子对光球的加热很可能声学发射的主要因素。

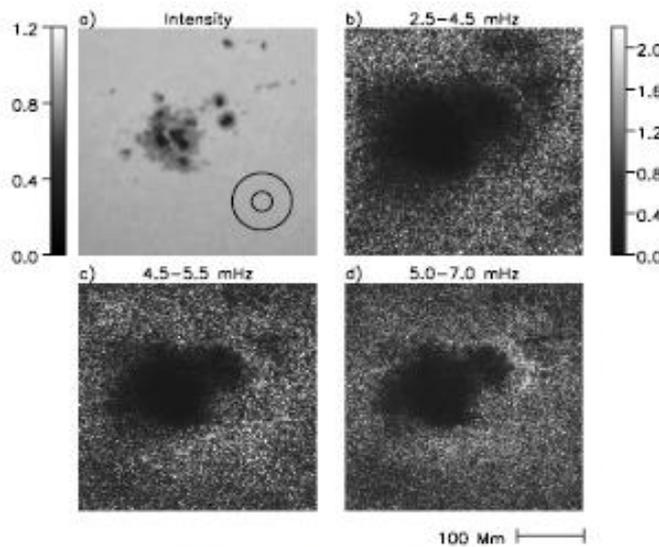


FIG. 2.—Ergation power maps of SOHO MDI Doppler observations of NOAA AR 10486 in three spectral passbands integrated over the time interval 10:00–12:00 UT. (a) A GONG intensity image taken at 11:11 UT, shortly prior to the flare. (b) Ergation power for sun-emit radiation over the 2.5–4.5 mHz passband. (c) Same as in (b) but for 4.5–5.5 mHz. (d) Same as in (b), but for 5.0–7.0 mHz. The annulus drawn in the lower right corner of panel (a) shows the dimensions of the passband (inner radius 15 Mm, outer radius 45 Mm), which is centered on each pixel for the ergation computations. A value of 1 in the ergation power maps corresponds to $250 \text{ m}^2 \text{ s}^{-3}$, which is the value of the ergation power averaged over a region of quiet Sun. [See the electronic edition of the Journal for a color version of this figure.]

图 3. 10: NOAA 10486 活动区 SOHO MDI 多普勒观测的 2.5 - 4.5 (b)、4.5 - 5.5(c)、5.0 - 7.0mHz(d)外出能量图, (a)GONG 强度

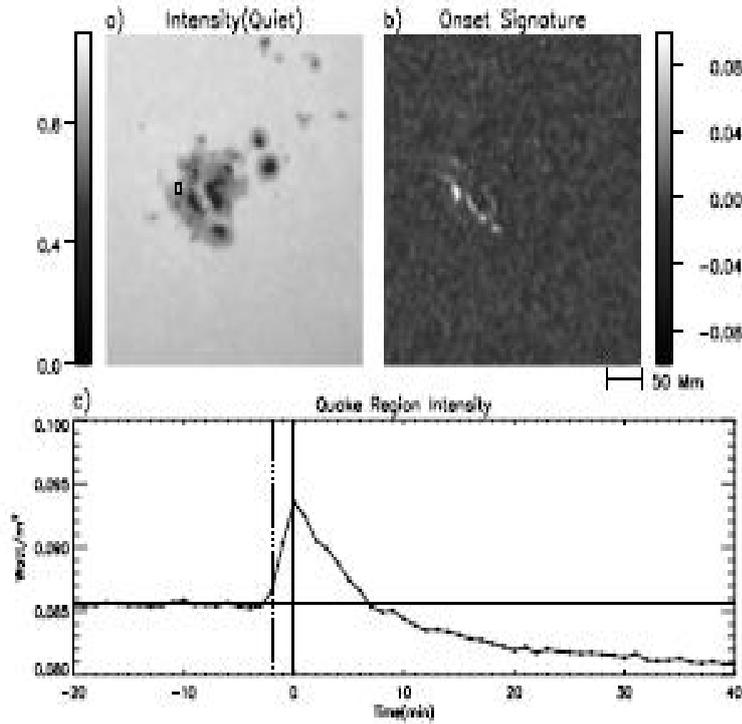


FIG. 9.—GONG intensity images in the photospheric $H\alpha$ 6563 Å line showing rapid intensity increase in the neighborhood of the seismic emission signature within 2 of the flare. (a) The intensity at 20:40 UT, just before the onset of the flare. (b) The difference between the intensity at 20:42 and 20:40 UT. (c) A plot of the mean averaged over the rectangular region plotted in panel (a), normalized to unity for the intensity of the quiet Sun at disk center. The solid vertical line in the plot in panel (c) represents 20:42 UT, which is referenced to zero on the abscissa. The dashed line indicates 20:40 UT, 2 minutes before, representing the preflare intensity image in panel (a).

图 3. 11: 在震动发射附近 GONG 强度显示快速增加

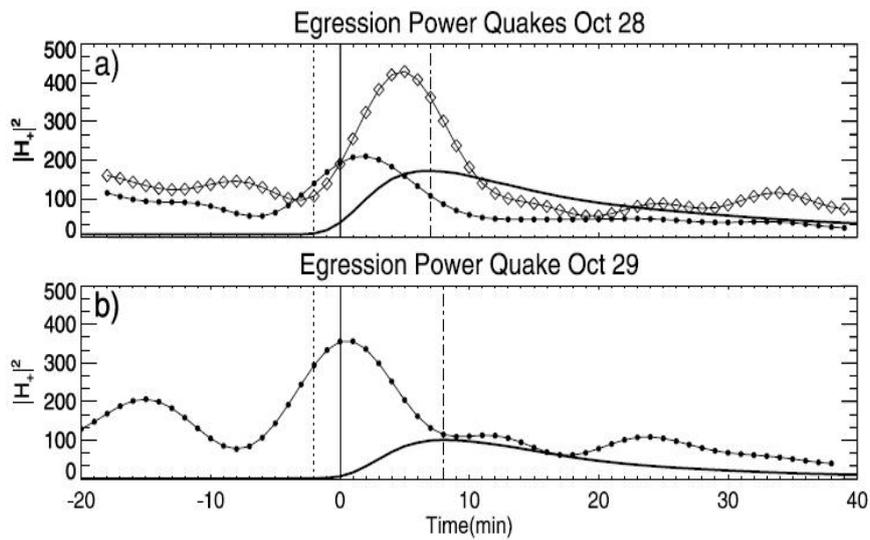


FIG. 12.—Plots of the 5–7 mHz acoustic emission in the seismic signatures of the (a) 2003 October 28 and (b) October 29 flares compared with the GOES-12 keV X-ray flux (in units of 10^5 W m^{-2} ; thick solid curves). (a) October 28 flare: The solid line with diamonds corresponds to the western acoustic source, whereas the solid line with filled circles corresponds to the eastern acoustic source of the flare. The solid vertical line represents 11:02 UT, which is referenced to zero on the abscissa. The dot-dashed line represents the time at which the GOES X-ray flux reached a maximum. (b) October 29 flare: Same as above, but the solid vertical line referenced to zero on the abscissa represents 20:42 UT.

图 3. 12: 声波发射特征

3.2.3. 2013 年 11 月 4 日巨大耀斑的硬 X 射线多航天器观测

Kane (2005, A&A, 433, 1133 - 1138) 利用多个航天器观测资料分析了 2013 年 11 月 4 日巨大耀斑产生的硬 X 射线辐射之间的关系。Ulysses 航天器位于太阳-地球线以西~114 度距离太阳 5.28 AU，其上的 X 射线/伽玛射线光谱仪观测到硬 X 射线辐射。地球附近 RHESSI 上的硬 X 射线成像仪观测到在该大耀斑上升早期一个小的硬 X 射线暴和一部分硬 X 射线衰退，由于 RHESSI 仪器处在行星之夜而不能观测到硬 X 射线的极大值。在 1943 - 1958 UT 期间，GOES 软 X 射线观测饱和，估计软 X 射线峰值在~1947 UT 可能达到 NOAA \geq X28 级别。OVSA 射电观测显示该耀斑产生了强微波辐射，~1945 UT 在 15.4 GHz 处达到~60000 sfu，在米波和分米波段报道了前 II、III 和 IV 型射电暴。1933 UT to 2015 UT 期间，Ulysses 观测到在 25 - 150 keV 能量段 X-射线的增强，与 15.4 GHz 射电辐射几乎同时，比软 X 射线极大值早 3 分钟。

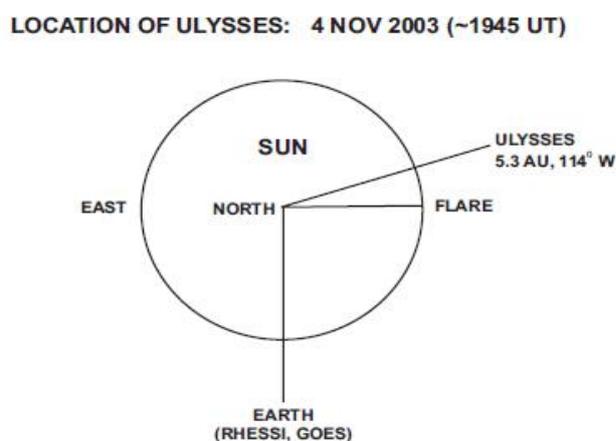


Fig. 1. The locations of the *Ulysses*, RHESSI and GOES spacecraft (projected onto the ecliptic plane) relative to the Sun-Earth line. The location of the 2003 November 4 flare on the solar disk is also shown.

图 3. 13: Ulysses, RHESSI 和 GOES 卫星位置

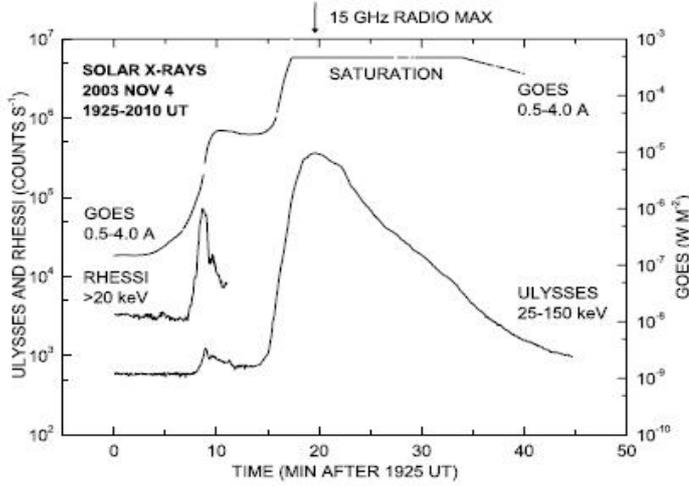


Fig. 2. From top to bottom, the time histories are shown for (1) the 0.5–4.0 Å X-ray emission observed by the GOES instrument, (2) the integral counting rate of 25–150 keV X-rays observed by the *Ulysses* instrument at the location of *Ulysses* (5.3 AU from the Sun), and (3) the integral counting rate of X-rays >20 keV observed by RHESSI. For reference, the time of maximum for the 15 GHz radio emission observed by the Owens Valley Solar Array (OVSA) is indicated by an arrow at the top of the figure. After 1936 UT RHESSI was close to satellite night and data are not shown.

图 3. 14: GOES 0.5 - 4.0 Å、Ulysses 25 - 150 keV X 射线观测和 RHESSI >20 keV 积分计数

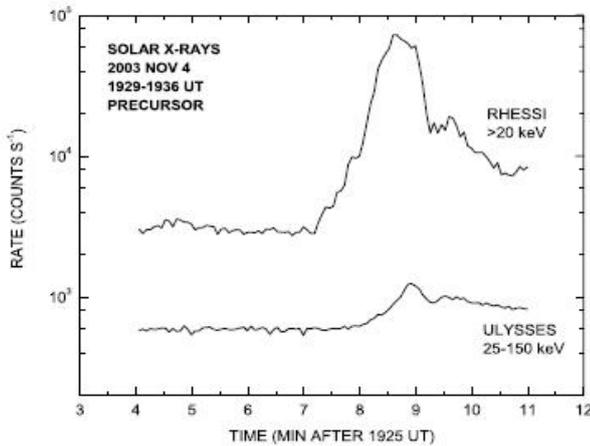


Fig. 3. The integral (25–150 keV) counting rate of the *Ulysses* instrument and the counting rate of X-rays >20 keV observed by RHESSI during the small hard X-ray burst associated with the 2003 November 4 solar flare.

图 3. 15: Ulysses 25 - 150 keV 积分计数和 RHESSI >20 keV X 射线计数 (2003, 11, 4)

3.2.4. 2003 年 10 月 28 日 CME 的三维 MHD 模拟: 与 LASCO 日冕观测比较

2003 年 10 月 28 日由 NOAA 10486 活动区爆发的 CME 不到 20 小时传到了地球, 并产生了一系列地磁暴事件, Manchester 等 (2008, APJ, 684, 1448-1460) 对该 CME 进行了数值模拟。从同一个活动区启动两个 CME, 一个比另一个大约早一天, 用以限制 28 日更快 CME 的太阳风, 第二个 CME 以超过 2500 km/s 的速度通过日冕, 驱动一个向前的强激波。他们在由 LASCO C3 产生的图像中清楚地识别出了该激波, 从模拟中再现合成白光图像中的激波及其外形, 无论在形态上还是亮度上, 发现 CME 模型与 LASCO 观测非常一致。说明 CME 形状主要由与周围环境的相互作用决定, 而与起始过程关系不大。

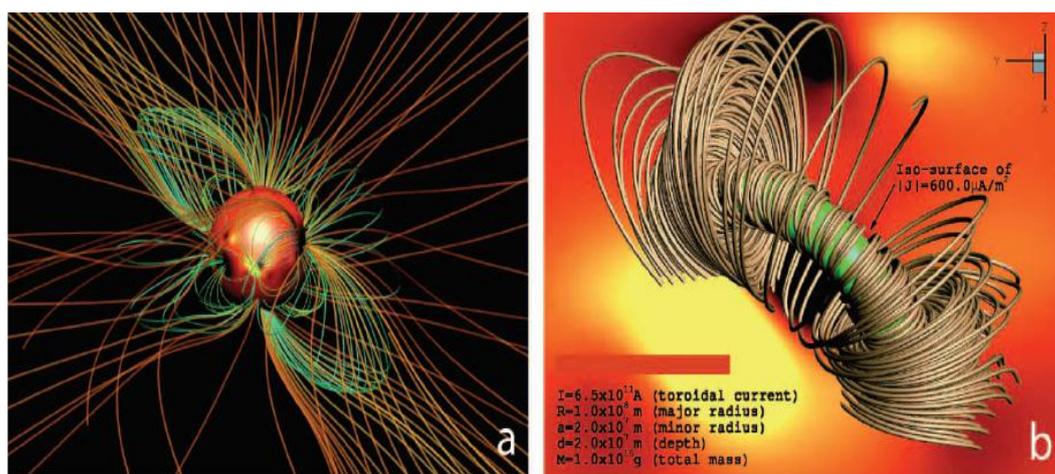


Fig. 1.—Initial condition of the corona for the October 28 CME. (a) Radial field strength, B_r , at the base of the corona. The structure of the coronal magnetic field is illustrated with blue and yellow lines for the closed field, while orange lines show the open field. (b) Closeup of AR 10486 with the superposed flux rope illustrated with field lines and a current density isosurface colored green.

图 3. 16: 10 月 28 CME 的初始条件

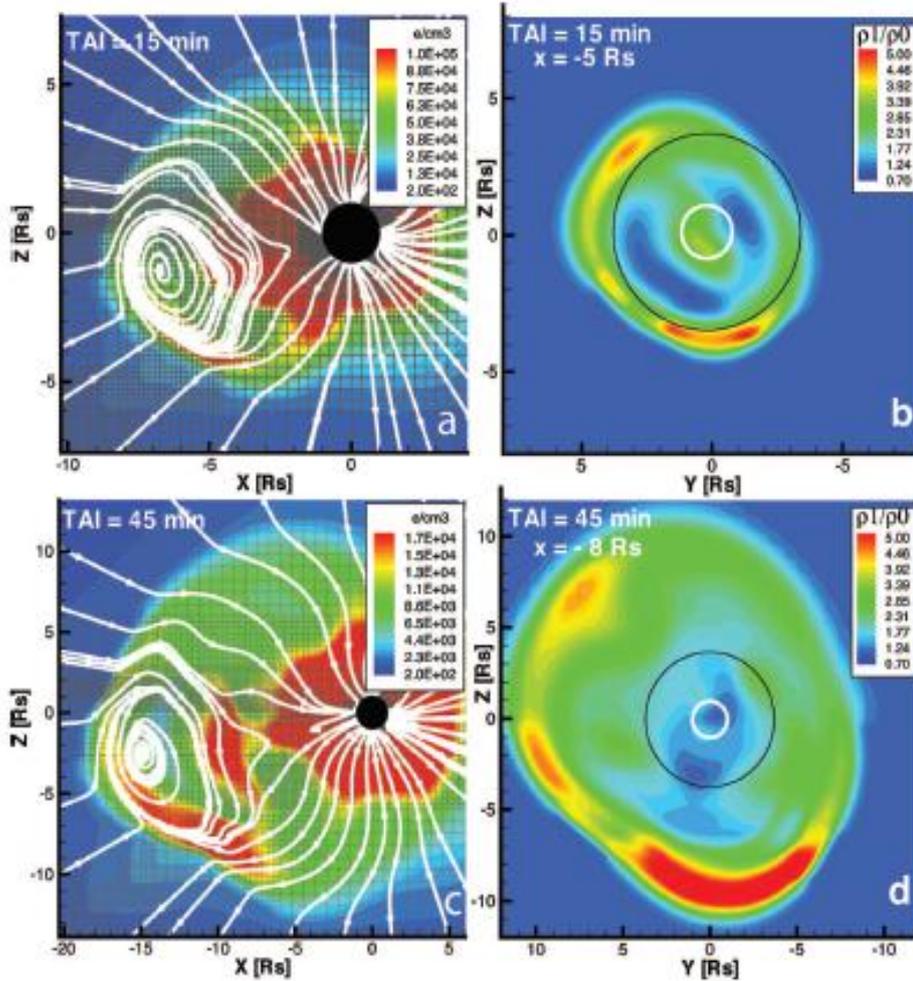


FIG. 2.—Structure of the CME at time after initiation equal to 15 and 45 minutes is shown in the top and bottom rows, respectively. (a, c) Electron density is shown in color with magnetic stream lines (confined to the plane) drawn white and the numerical mesh drawn black. These images show the ejected magnetic flux rope traveling toward the Earth in the $-x$ direction with the center of the rope and density kerna concentrations below the equatorial plane. (b, d) Ratio of the density relative to the previous state on $y-z$ plane positioned near the center of the CME at $x = -5$ and $-8 R_{\odot}$, respectively. The white and black circles are drawn at 2 and $3.7 R_{\odot}$, respectively, corresponding to the occulting disks of C2 and C3, respectively. These images show the greatest density enhancement at the bottom ($-z$) of a nearly circular shell-type structure that evolves in a self-similar fashion.

图 3. 17: 15 (上) 和 45 (下) 分钟之后 CME 的形状, 左图为电子密度, 右图为相对密度

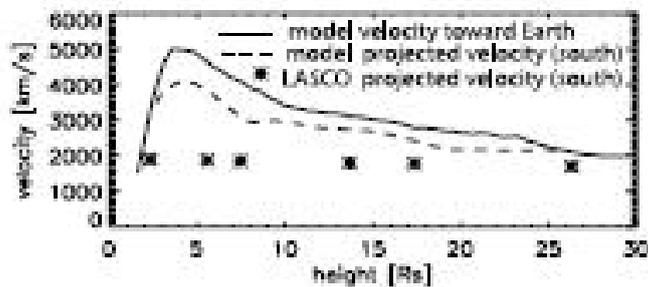


FIG. 4.—Comparison of observed and modeled CME velocity. The solid line shows the modeled CME velocity moving directly toward the Earth, while the dashed line shows the model velocity projected on the plane of the sky 1.77° (counterclockwise) to the north-polar axis. At this same location in the plane of the sky, the CME velocity is derived from LASCO observations and plotted with stars. We find that the model briefly reaches an velocity of 4000 km s^{-1} at $4.5 R_{\odot}$ before falling to 2000 km s^{-1} at $20 R_{\odot}$. In contrast, the CME is observed to decelerate from 1699 to 1699 km s^{-1} as it travels from 2.3 to $26.3 R_{\odot}$.

图 3. 18: 模型与 LASCO 观测的 CME 速度比较

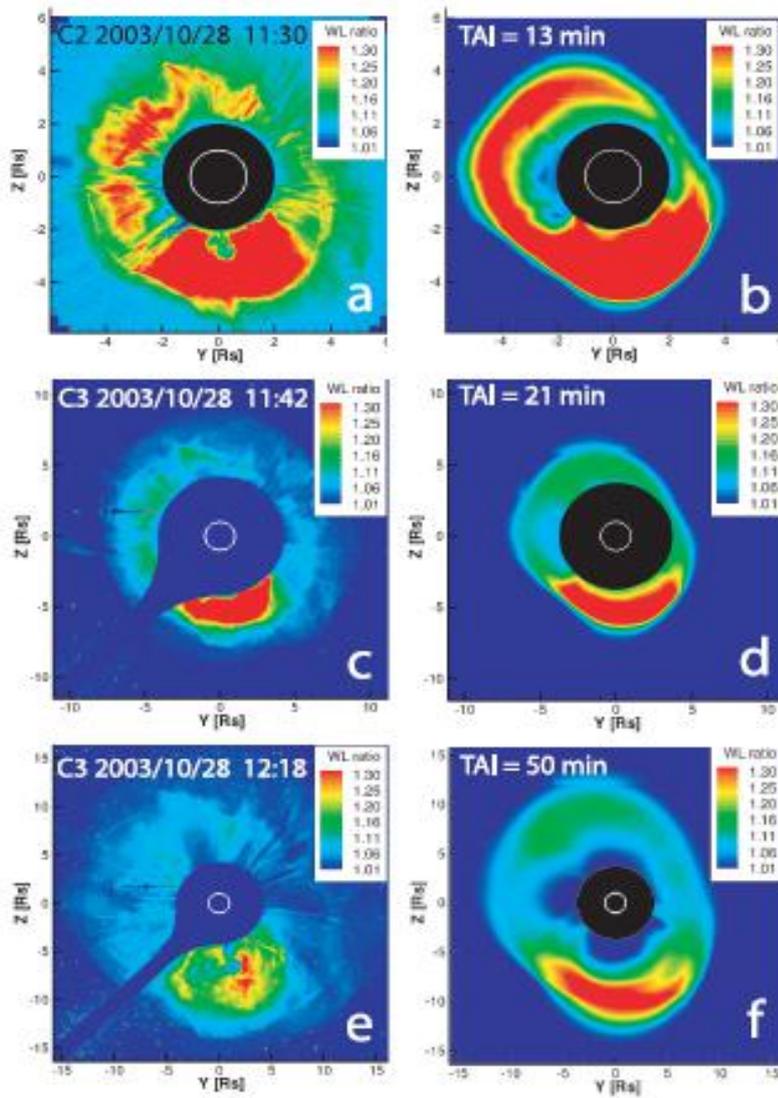


FIG. 5.— Comparison of observed (left) and simulated (right) Thomson-scattered white-light brightness. The color images show the total brightness divided by that of the pre-event background. White circles show the solar limb, and filled black circles show occulting disks. (a) LASCO C2 observation at 11:30 UTC. (c, e) LASCO C3 observations at 11:42 and 12:18, respectively. (b, d, f) Model coronagraph images at 13, 21, and 50 minutes after initiation. Here we find that the model achieves remarkable quantitative agreement with both the magnitude and spatial distribution of the observed brightness.

图 3. 19: 观测 (左) 与模拟 (右) 汤姆孙散射白光亮度比较

3.2.5. 2003 年 10 月 28 日 X17 耀斑的伴随事件及前兆

NOAA10486 活动区发生的耀斑是一个双带耀斑，伴随暗条爆发及快速日冕物质抛射。Mandrini 等（2006, *Solar Physics*, 238, 293 - 312）分析了该耀斑之前及期间的磁场 (SOHO/MDI), 色球(NainiTal 观测及 TRACE)及日冕事件 (TRACE), 结合日冕磁场模型, 主要研究耀斑开始前的两个事件, 一个事件在耀斑前一小时被 TRACE 观测到, 与日冕磁零点的局部磁重联有关, 该事件与大耀斑寿命同样长, 因此, 两者可能无关。第二个事件与第一个同时发生, 在 $H\alpha$ 及 TRACE 像中可见, 涉及一个大规模四极重联, 该重联造成磁张力的减少, 这样可使暗条以爆发模型提出的方式爆发, 但磁重联发生在准分割层(QSLs)而不是在磁零点。

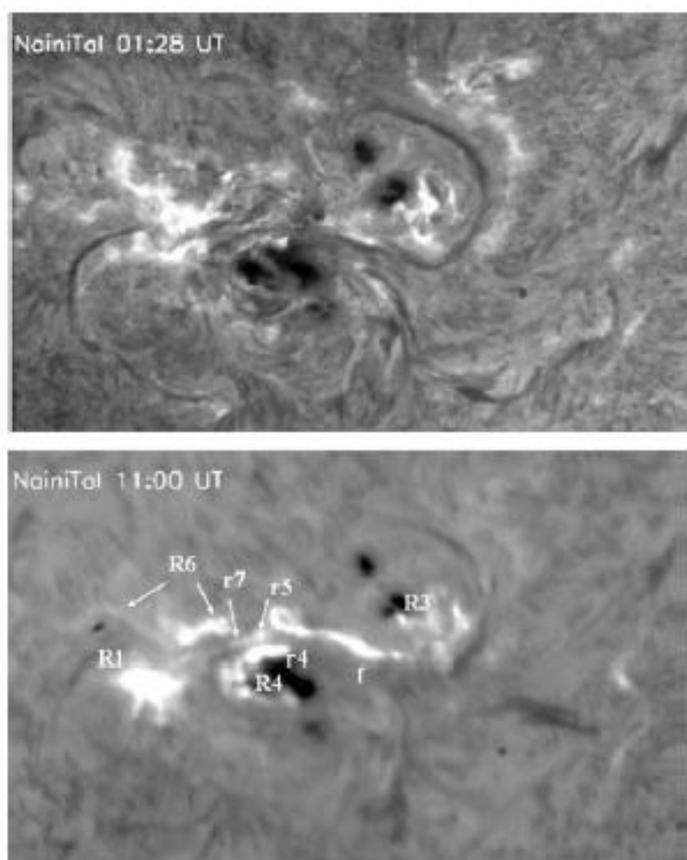


Figure 2. Images showing a large-scale view of the AR in $H\alpha$. An elongated sigmoidal filament is seen on the top, the eruption of its central portion accompanies the two-ribbon X17 flare. The image at the bottom shows the $H\alpha$ ribbons with their associated label starting with "R" and "r" for those associated with a large-scale event (Section 2.3) and a small-scale event (Section 2.4), respectively. The number in the ribbon label indicates the magnetic polarity defined in Figure 1. "r4" has merged with "R4" in this image and other brightenings are present to the west of "R3" (compare to Figure 3). The letter "f" refers to the heated filament plasma.

图 3. 20: $H\alpha$ 观测的活动区: 长 S 型暗条 (上), 大规模事件 (R) 与小规模事件 (r)

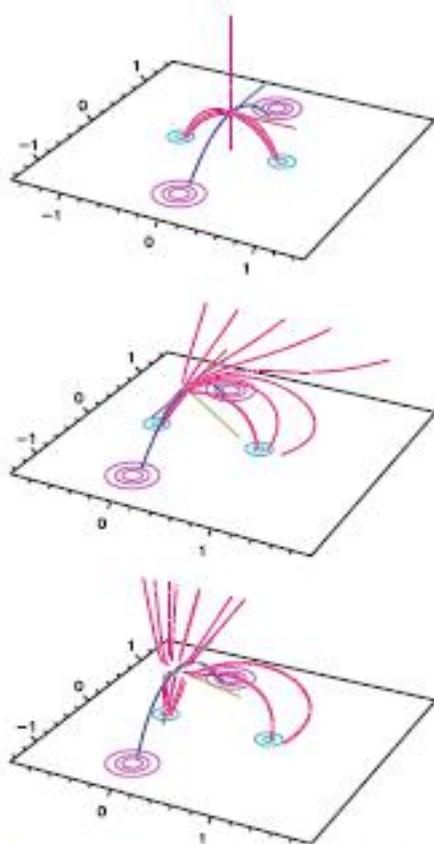


Figure 6. Coronal magnetic configuration in the vicinity of null points. The three panels correspond to the theoretical configurations (models 1, 2 and 3, respectively) discussed in Section 3.3. The three segments at the null locations correspond to the direction of the three eigenvectors of the Jacobian field matrix. The colors of the segments are indicative of the magnitude of each eigenvalue: red (yellow) corresponds to the largest (lowest) eigenvalue in the fan plane and blue to the spine eigenvalue. The yellow segment is vertical in the top figure and is overlapped with the red field line due to the symmetry of the configuration. The sign direction of the red and blue eigenvectors are reversed in the second panel, as compared to the other two, for better visualization. The red magnetic-field lines are drawn in the fan plane, while the blue line is the spine (all starting close to the null). In all figures the negative (positive) field isocountours are shown in blue (pink).

图 3. 21: 磁零点附近的磁场构型。

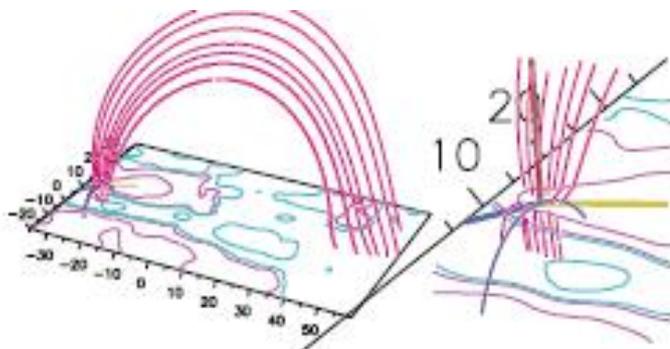


Figure 7. The left panel shows the magnetic null point in the observed AR 10486 coronal field. Field lines are starting in the close vicinity of the null point as in Figure 6. The right panel is an enlargement at the null location in which the direction of the three eigenvectors of the Jacobian field matrix are better seen. The axes are colored following the same convention as in Figure 6. The negative (positive) field isocountours are shown in blue (pink), their values are $\pm 100, 1000$ G.

图 3. 22: NOAA10486 活动区观测到的磁零点

3.2.6. 2003 年 10 月 28 日太阳事件产生的相对论核子与电子

2003 年 10 月 28 日太阳耀斑在地球产生了一个相对论粒子，Miroshnichenko 等 (2004, JGR, 110, A09S08) 分析了该事件中高能粒子在太阳上的加速及到地球的传播性质，认为不同从中子观测站数据来看，最早到达的粒子是核子，几分钟之后到达了第一个相对论质子。有两类相对论太阳质子 (RSP): 瞬时的与延迟的，前者引起了一个脉冲增强，后者比前者晚半小时，两者都是从反太阳方向到达。由米波到千米波 (Wind/WAVES) 射电辐射跟踪的亚相对论电子在太阳西半球面伴随米波射电辐射，距离耀斑活动区很远。他们认为地球处在行星 CME (ICME) 与共转流的交界面上，在这种情形下，高能质子与电子在耀斑区加速，注入到根植于活动区的 ICME 环东边足上，在通过环顶点后从反太阳方向到达地球。而瞬时逃逸的亚相对论电子是在太阳西半球面加速且按照正常的 Parker 螺旋传播。

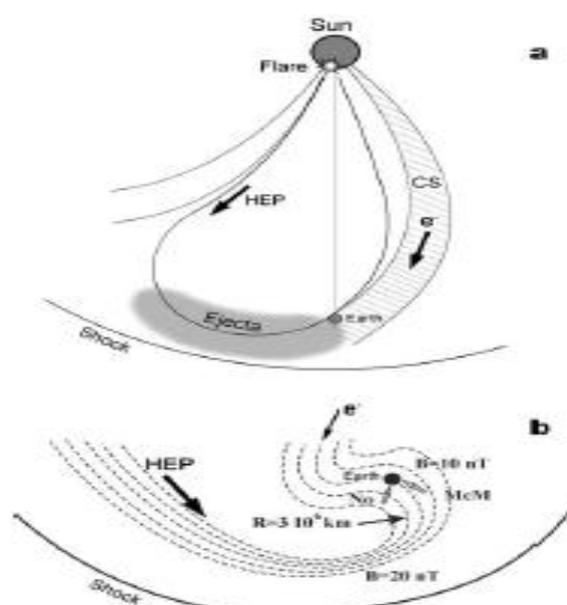


Figure 9. (a) Sketch of the proposed model for the IMF structure during the 28 October, 2003 SPE. The Earth is at a boundary area between an ejecta from the flare 26 October and the co-rotating stream (CS) commenced to Earth shortly before the event. By means of looped IMF structure inside ejecta, the Earth is connected to a flare site in eastern part of solar disc. High-energy solar protons (HEP) come to the Earth from antisunward direction. At the same time, the subrelativistic electrons can arrive to the Earth from a source in western part of solar disk along of a Parker spiral IMF line, connected with a co-rotating stream. (b) The spatial structure of IMF near the Earth during the 28 October 2003 GLE, reconstructed with use of IMF⁺ and solar wind data. The dotted lines are the IMF field lines and arrows are average directions of relativistic proton flux registered by neutron monitors in McMurdo (McM) and Nodak (No). By essential detail here is the sharp kink of a magnetic field with the radius of curvature $3 \times 10^6 \text{ km}$ compatible with Larmor radii of relativistic solar protons.

图 3. 23: IMF 模型

表 3. 1: 不同牛顿监测仪测量的地面增强事件 (GLE)

Table 1. Onset Times of the GLE Measured By Different Neutron Monitors

Stations	Location	Altitude, m	R_c , GV	Sun's Declination Angle	Peak Intensity, %	Onset Time, UT
Tsumeb	20S 18E	1240	9.21	79°	5	1105 ± 1
South Pole	90S 00E	2820	0.09	13°	18	1120 ± 1
McMurdo	80S 167E	48	0.00	2°	47	1118 ± 1
Norilsk	69N 88E	0	0.58	-9°	25	1112 ± 1
Moscow	57N 37E	200	2.40	17°	15	1114 ± 1
Terre Adelle	67S 140E	32	0.00	-3°	29	1112 ± 1

3.2.7. 大耀斑相对磁螺度的变化

Park 等 (2008, APJ, 686, 1397-1403) 利用 SOHO/MDI 事件分析了包括 NOAA10486 在内的 7 个活动区产生的 11 个 X 级耀斑的磁螺度变化, 发现: 1) 在这些大耀斑之前螺度有一个长时间积累 (0.5 到几天); 2) 螺度接近似一常数速率 ($4.5-48 \times 10^{40} \text{ Mx}^2/\text{hr}$) 积累, 之后在耀斑之前变为常数。正如所料, 螺度积累量与耀斑期间 X 射线流量的时间积分存在中等的相关性, 而平均螺度变化率与 X 射线流量时间积分相关性更高, 这种螺度变化形状可以作为统一爆发的早期警报信号。

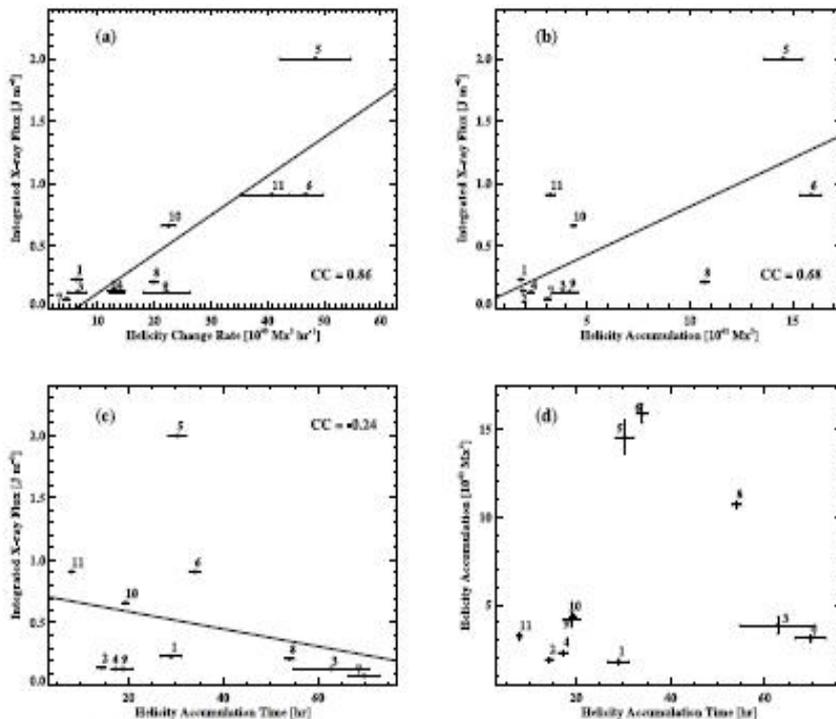


FIG. 4.—Helicity parameters with GOES X-ray flux integrated over the flaring time. Correlations of the integrated soft X-ray flux with (a) average helicity change rate of phase I, (b) the amount of helicity accumulation during phase I, and (c) helicity accumulation time. The correlation coefficient (CC) is specified in each panel. In (d) the amount of helicity accumulation is plotted as a function of the accumulation time. The uncertainties of the average helicity change rate, the amount of helicity accumulation, and the helicity accumulation time are shown as error bars in each panel.

图 3. 24: 螺度积分参量。积分通量与螺度变化率相关性最高 (0.86)

3.2.8. 三个 X 级耀斑后半影的迅速衰退

Wang 等 (2004, APJ, 601, L195 - L198) 发现三个 X 级耀斑之后半影迅速衰退现象, 半影衰退的轨迹与耀斑辐射有关, 图像差分显示半影衰退而本影变得更黑, 认为在耀斑之后大约一小时后磁场从高度倾斜变为更垂直形状, 或者说, 一部分半影磁场转变为本影磁场。

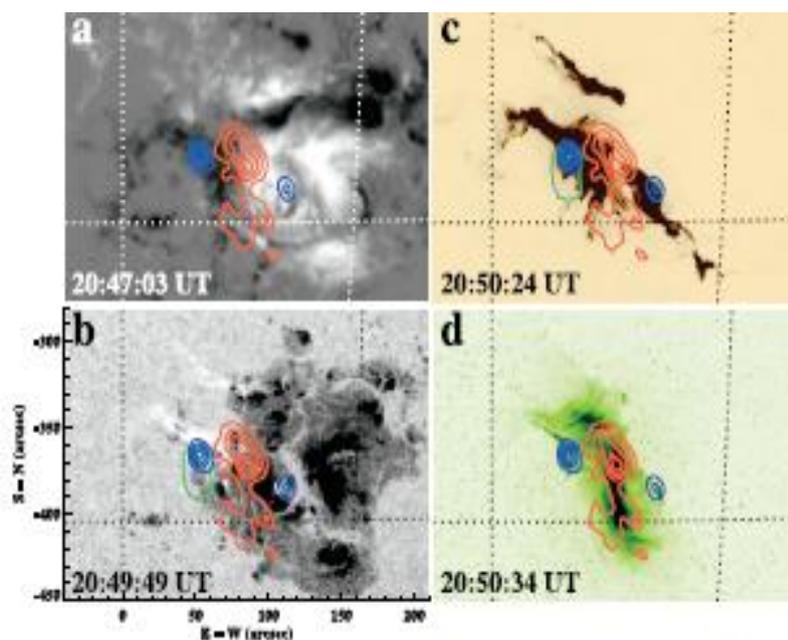


FIG. 2.—RHESSI hard X-ray contours corresponding to the 15–20 keV channel (red) and 50–100 keV channel (blue) for the X10 flare on 2003 October 29 superposed on (b) TRACE white light, (c) 1600 Å, and (d) 195 Å images and an MDI magnetogram (a). Note that TRACE 1600 and 195 Å intensities are presented by negative images. RHESSI maps were accumulated from 20:49:42 to 20:50:42 UT. Contour levels correspond to 30%, 50%, 70%, and 90%, respectively. The two footpoints and a loop top source are clearly discernible. The decayed penumbra is indicated by the green contour in (b) and (c).

图 3. 25: RHESSI 硬 X 射线 15 - 20 keV (红) 及 50 - 100 keV (蓝) 轮廓, 叠加在 (a) MDI, (b) TRACE 白光像, (c) 1600, (d) 195 像上, 衰变的半影轮廓由绿线表示

3.2.9. 2003 年 10 月 29 日耀斑在 1.56 微米处的近红外观测

Xu 等 (2004, 607, L131 - L134) 分析了 2003 年 10 月 29 日在萨克拉门托峰国家太阳观测站邓恩望远镜观测到的 10486 活动区 X10 级白光耀斑, 用 1.56 微米处的近红外 (NIR) 观测研究其动力学行为, 与 RHESS/HXR 及 SOHO /MDI 数据进行了对比。在耀斑脉冲相期间, 两个耀斑带分离, 无论在时间上还是在空间上都与 RHESSI HXR 带相关。

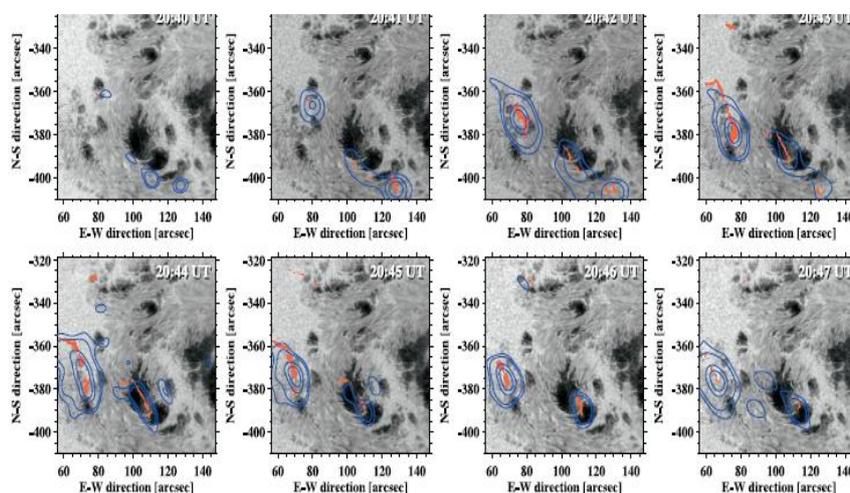


Fig. 2.—NIR time sequence of the X10 flare from 20:40 to 20:47 UT on 2003 October 29. RHESSI HXR contours (blue) correspond to the 50–100 keV channel with 60 s integration. The local NIR intensity maxima are shown in red. Two flare ribbons are correlated with strong HXR kernels. HXR contour levels are drawn at 0.17, 0.25, 0.60, and 0.80 of the maximum intensity, except for the first two frames, where they correspond to 0.7 and 0.8 for the first frame and 0.4, 0.6, and 0.8 for the second, when the HXR kernels were weaker.

图 3. 26: NIR 序列。蓝线为 RHESSI HXR 50 - 100 keV 通道, 红线为 NIR 最大强度

3.2.10. 沿着磁中性线的光球剪切流动

Yang 等 (2004, APJ, 617, L151 - L154) 采用高适应光学系统、框架选择及掩饰方法, 分析了 2003 年 10 月 29 日在萨克拉门托峰国家太阳观测站邓恩望远镜观测到的 10486 活动区 X10 级白光耀斑之前两小时的自行运动, 用局部相关跟踪方法测量光球自行运动, 发现了沿磁中性线的强剪切流, 这些剪切流域可见及红外的白光耀斑核相关。

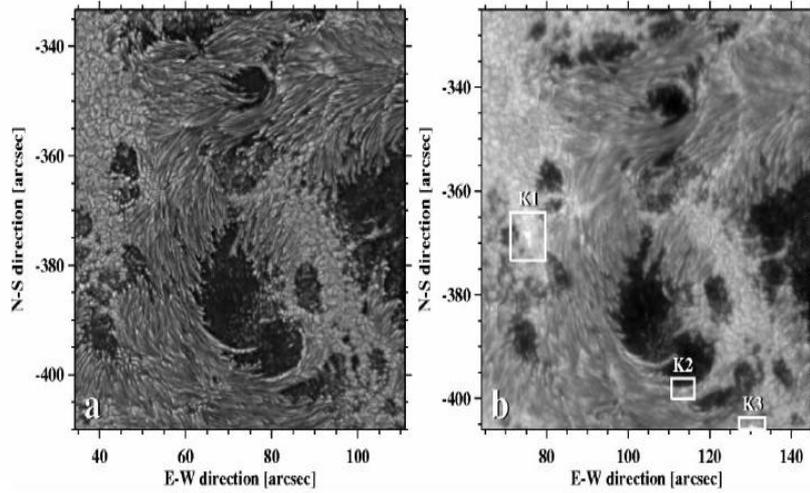


FIG. 1.—White-light continuum images of solar NOAA AR 10486 were obtained on 2003 October 29. (a) A speckle-reconstructed image showing the preflare state at 16:59 UT and (b) a frame-selected image at 20:44 UT depicting the white-light flare kernels outlined by three white boxes.

图 3. 27: NOAA AR 10486 活动区白光像。(a) 斑点重构图显示耀斑前状态；(b) 框架选择图像显示白光耀斑核

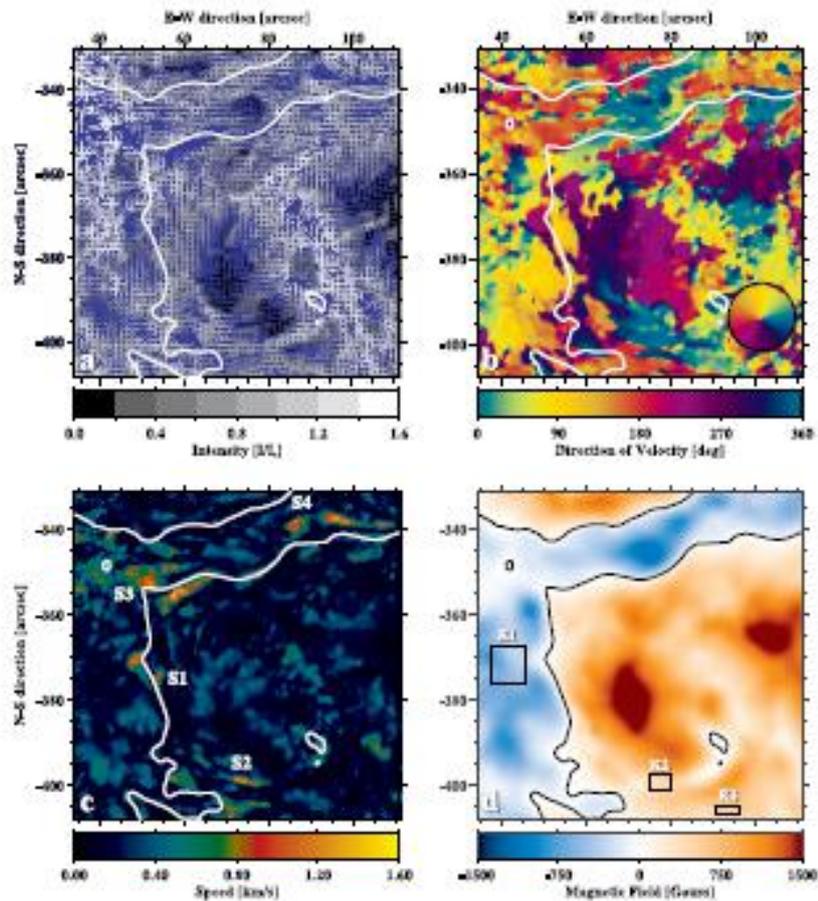


FIG. 2.—Photospheric flows and magnetic field configuration of NOAA AR 10486 on 2003 November 29. To illustrate the high spatial resolution LCT results, we provide different views of (a) flow vectors, (b) azimuth angle of the velocity vectors, (c) magnitude of the velocity vectors, and (d) MEI magnetogram with superposed magnetic neutral lines.

图 3. 28: NOAA 10486 活动区的光球流

3.2.11. 旋转黑子与耀斑的关系

Zhang 等 (2008, Solar Phys, 247, 39 - 52) 分析了正极黑子的主轴旋转运动的演化及特性, 估计他们注入的螺度积累, 同时分析了发生在旋转黑子周边的同源耀斑。重要结论为: i) 在活动区正极性的主轴上存在逆时针旋转运动; ii) 从旋转运动得出的螺度注入与用局部相关跟踪方法得出的量相当; iii) 两个与 CME 相关的同源耀斑的始发与黑子的旋转运动在时间及空间上相关。因此, 黑子的旋转运动不仅与从低层大气到日冕的磁能与复杂性转变有关, 还对同源耀斑的触发起到了关键作用。

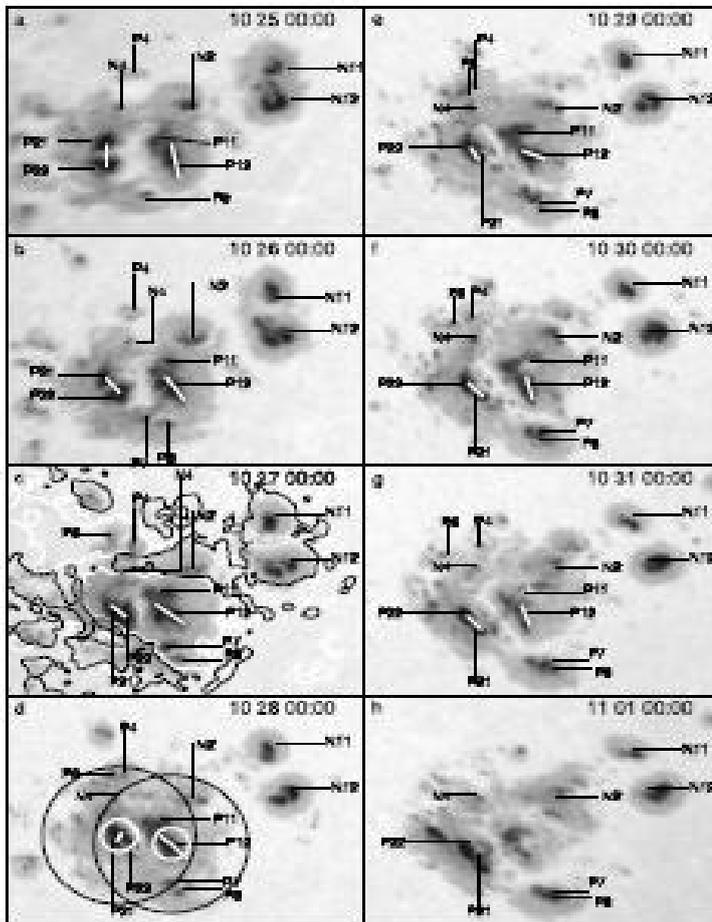


Figure 1. A time sequence of MDI intensitygrams showing sunspot evolution clearly. The image of 27 October is overlaid by a longitudinal magnetogram of MDI. White contours represent positive polarity; black represent negative. The preceding (negative) sunspots are marked with N and following (positive) are marked with P. White bars show the long axis of sunspot P12 and the connecting line of the weighted center of the pair of sunspots P21 and P22. White dots in Figure 1d represent the barycenters of the rotating sunspots. White circles outline the rotating sunspots and black circles indicate the radius of occurring sunspots shown in Figures 3 and 4. The field of view is $280^{\circ} \times 200^{\circ}$.

图 3. 29: MDI 磁图显示黑子演化

Figure 2 Angular speed of sunspots as a function of date.

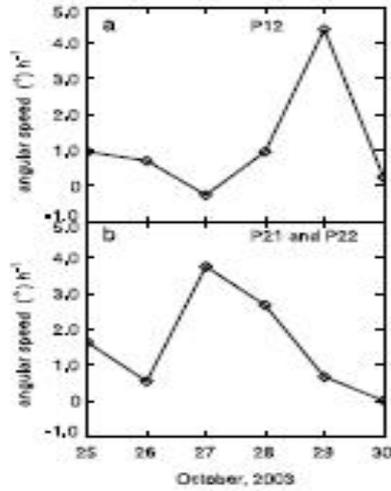


图 3.30: 角速度变化

Figure 3 Variation of the helicity sign of NOAA AR 10486 for five successive days. Error bars refer to 1 σ of sign.

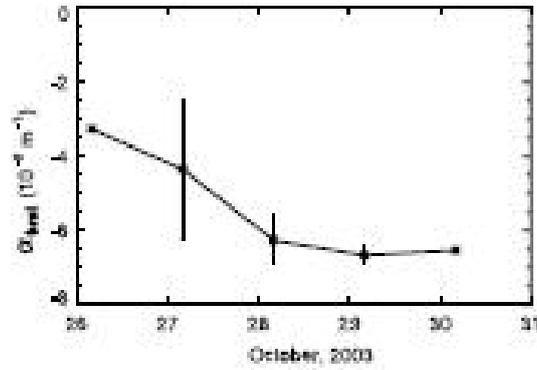


图 3.31: 螺度变化

表 3.2: 由黑子旋转运动注入的磁通、角速度及螺度

Table 1 Magnetic flux, angular speed, and helicity injected by rotational motion of sunspots.

Date	P12			P21 and P22			Total
	Φ (10^{21} Mx)	ω ($^{\circ}$ h $^{-1}$)	$\frac{dH}{dt}$ (10^{40} Mx 2 h $^{-1}$)	Φ (10^{21} Mx)	ω ($^{\circ}$ h $^{-1}$)	$\frac{dH}{dt}$ (10^{40} Mx 2 h $^{-1}$)	$\frac{dH}{dt}$ (10^{40} Mx 2 h $^{-1}$)
25	3.5	0.96	-3.74	4.3	1.63	-9.56	-13.30
26	4.0	0.71	-3.57	4.7	0.54	-3.80	-7.37
27	5.4	-0.25	+2.32	5.9	3.75	-41.57	-39.25
28	5.0	0.96	-7.64	5.3	2.67	-23.89	-31.53
29	4.3	4.38	-25.79	4.8	0.67	-4.92	-30.71
30	4.1	0.25	-1.30	4.5	0.00	0	-1.30
Total		168 $^{\circ}$	-1.0×10^{43} Mx 2		222 $^{\circ}$	-2.0×10^{43} Mx 2	-3.0×10^{43} Mx 2

3.2.12. NOAA 10486 发生的 X17.2 耀斑: 骨牌效应产生暗条不稳定的例子

存在两种模型来描述爆发耀斑:一种是标准模型,假定多数能量在剪切磁场的核心区被磁重联释放;另一种是爆发模型,假定重联首先发生在与爆发现象重叠的磁拱处。Zuccarello 等(2009, A&A, 493, 629 - 637)利用射电数据(0.8 - 4.5 GHz)、白光像(WL 及 $H\alpha$)、EUV 图像(1600 和 195 Å)、X 射线数据、及 MDI 纵向磁图,进行了多波段分析。结果发现,该活动区有多个拱,在 X17.2 耀斑前一个暗条发生了部分爆发,该爆发引起了低层大气磁零点处的重联及与其它暗条重叠的日冕磁场张力的减少,结果这些暗条失去稳定并导致耀斑发生。因此,NOAA 10486 耀斑不能有一个简单的标准模型或爆发模型解释,而是由所谓骨牌效应引起,涉及到一系列不稳定过程触发耀斑。

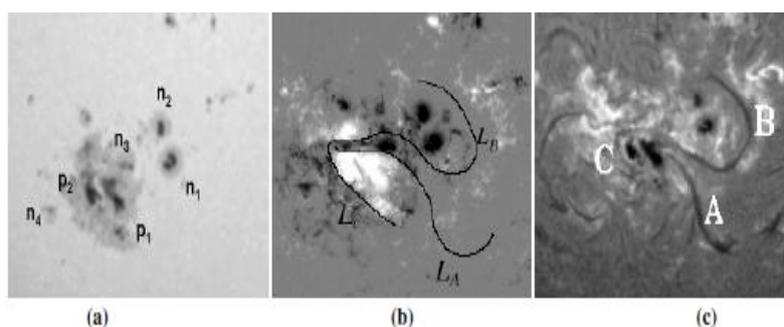


Fig. 1. a) Photospheric image of NOAA 10486 acquired at INAF-OACT on 28 October at 8:29 UT; n_1, n_2, n_3 and n_4 indicate the sunspots of negative polarity, while p_1 and p_2 are the main positive polarity spots; b) MDI magnetogram showing the magnetic configuration of NOAA 10486 at 08:00 UT; L_A, L_B and L_C indicate the main neutral lines; c) $H\alpha$ image acquired at INAF-OACT at 7:37 UT. The labels A, B, and C indicate three filaments involved in the flaring activity of NOAA 10486 that are located along the neutral lines L_A, L_B , and L_C , respectively. The field of view of these images is $\sim 335 \times 335 \text{ Mm}^2$. In these and in the following images, if not specified otherwise, North is at the top, West at the right.

图 3. 32: (a)白光像, (b)MDI 磁图, (c)Ha 图

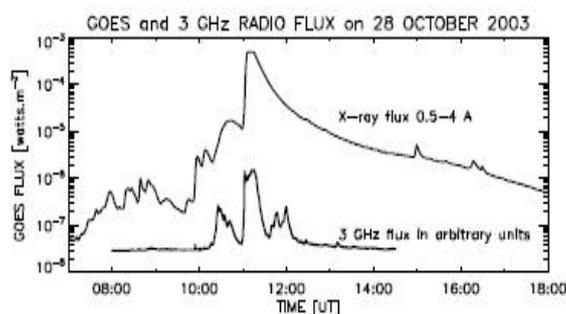


Fig. 2. GOES-11 recorded X-ray flux in the 0.5–4 Å band on 28 October 2003 together with the 3 GHz radio flux recorded by the Ondřejov radiospectrograph. The graph shows the occurrence of an X17.2 flare, with a peak of intensity at 11:10 UT.

图 3. 33: X 射线流量与射电流量

表 3. 3: 由 Potsdam-Tremsdorf 射电频谱仪观测的 40-80MHz 射电暴

Table 1. Radio-burst activity in the 40–800 MHz frequency range at 07:45–11:00 UT observed by the Potsdam-Tremsdorf radiospectrograph (Courtesy of Aurass).

Time interval (UT)	Frequency interval (MHz)	Burst types
10:42–10:48	400–800	group weak type III bursts
07:45–10:15	200–400	type III burst noise storm negatively drifting chains
10:15–11:00	200–500	group of strong type III bursts
07:45–07:48	50–75	type III burst
08:53–08:56	40–80	group of type III bursts
10:00–11:00	40–85	group of type III bursts

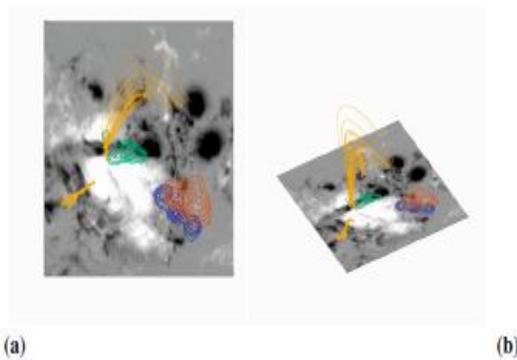


Fig. 12. Magnetic field lines and null points overplotted on the MDI magnetogram acquired at 07:53 UT: the null point 1 (see text) is located in the proximity of the negative intrusion, while the null point 2 is located on the eastern side of filament C; **a)** and **b)** show two different views of the MDI magnetogram with the locations of the null points and the hard X-ray sources at 07:55:42 UT (blue), 08:16:30 UT (green), and 11:22:08 UT (red-brown).

图 3. 34: 磁力线与磁零点

3.3. 主要科学贡献

2003 年 10 月 23 日到 11 月 5 日 NOAA 10486 活动区是“万圣节”事件最为活跃的活动区，产生了 9 个 X 级耀斑，其中包括有史以来最强的耀斑 (X28)，还产生了 12 个大型 CME 事件，最高速度超过了 2000 km/s，其中在 2003 年 10 月 28 日，10486 活动区产生了一个 X17.2 级耀斑，伴随了一个高速 CME。随后产生的高能粒子事件在 12:42 到达近地空间，导致 SOHO/LASCO/C3 的饱和而产生雪花效应。10 月 28 日的 CME 对地效应非常显著，11 月 4 日的 CME 是“万圣节”事件中最强的高能事件。NOAA 10486 的产生和演化对于基础太阳物理研究以及空间天气事件的预报都是很好的研究案例。国内外研究人员对该活动区进行了多方位的研究，使用的数据包括多波段的成像以及流量数据，包括磁场、极紫外、白光、近红外及射电等，研究了该活动区的磁能变化，产生的耀斑及 CME，以及相关爆发活动的行星际、对地效应。

● 多波段成像综合成像研究

➤ 流场的多波段研究

运用局部相关跟踪方法，分析了 NOAA10486 活动区的水平活动场，在 X10 耀斑出现前，沿磁中性线观测到了长时间持续水平及垂直剪切流动，流动方向没有变为指向更高的光球，在剪切运动区域流动速度减弱，而在没有剪切运动的区域，流动速度随高度增加。在 X10 耀斑之后，磁场梯度增加了，而在中性线附近，水平及垂直剪切流动大大提高了。这意味着，在耀斑之后，在中性线附近的光球剪切流动及局部磁场剪切可能会增加，正说明剪切或缠绕带的能量释放。

➤ 太阳耀斑的震动辐射

分析了 2003 年 10 月 28-29 日 NOAA10486 活动区的震动波，用日震图像方法来看波的震动源，钠 D1 发射线 (k6768) 观测显示在耀斑起始存在向下传播的激波/凝结现象，多数耀斑并不是声学活跃的，由高能粒子对光球的加热很可能声学发射的主要因素。

➤ 巨大耀斑的硬 X 射线多航天器观测

利用多个航天器观测资料分析了 2013 年 11 月 4 日巨大耀斑产生的硬 X 射线辐射之间的关系。Ulysses 航天器位于太阳-地球线以西~114 度距离太阳 5.28 AU，其上的 X 射线/伽玛射线光谱仪观测到硬 X 射线辐射。地球附近 RHESSI 上的硬 X 射线成像仪观测到在该大耀斑上升早期一个小的硬 X 射线暴和一部分硬 X 射线衰退，由于 RHESSI 仪器处在行星之夜而不能观测到硬 X 射线的极大值。在 1943 - 1958 UT 期间，GOES 软 X 射线观测饱和，估计软 X 射线峰值在 ~1947 UT 可能达到 NOAA \geq X28 级别。OVSA 射电观测显示该耀斑产生了强微波辐射，~1945 UT 在 15.4 GHz 处达到~60000 sfu，在米波和分米波段报道了前 II、III 和 IV 型射电暴。1933 UT to 2015 UT 期间，Ulysses 观测到在 25 - 150 keV 能量段 X-射线的增强，与 15.4 GHz 射电辐射几乎同时，比软 X 射线极大值早 3 分钟。

➤ 耀斑在 1.56 微米处的近红外观测

用 1.56 微米处的近红外 (NIR) 观测研究耀斑动力学行为，在耀斑脉冲相期间，两个耀斑带分离，无论在时间上还是在空间上都与 RHESSI HXR 带相关。

● 物理现象及参量研究

➤ 耀斑的伴随事件及前兆

分析了该耀斑之前及期间的磁场 (SOHO/MDI), 色球(NainiTal 观测及 TRACE)及日冕事件(TRACE), 结合日冕磁场模型, 主要研究耀斑开始前的两个事件, 一个事件在耀斑前一小时被 TRACE 观测到, 与日冕磁零点的局部磁重联有关, 该事件与大耀斑寿命同样长, 因此, 两者可能无关。第二个事件与第一个同时发生, 在 $H\alpha$ 及 TRACE 像中可见, 涉及一个大规模四极重联, 该重联造成磁张力的减少, 这样可使暗条以爆发模型提出的方式爆发, 但磁重联发生在准分割层(QSLs)而不是在磁零点。

➤ 大耀斑相对磁螺度的变化

分析了包括 NOAA10486 在内的 7 个活动区产生的 11 个 X 级耀斑的磁螺度变化, 发现: 1) 在这些大耀斑之前螺度有一个长时间积累 (0.5 到几天); 2) 螺度接近一常数速率($4.5-48 \times 10^{40} \text{ Mx}^2/\text{hr}$) 积累, 之后在耀斑之前变为常数。正如所料, 螺度积累量与耀斑期间 X 射线流量的时间积分存在中等的相关性, 而平均螺度变化率与 X 射线流量时间积分相关性更高, 这种螺度变化形状可以作为统一爆发的早期警报信号。

➤ 三个 X 级耀斑后半影的迅速衰退

发现三个 X 级耀斑之后半影迅速衰退现象, 半影衰退的轨迹与耀斑辐射有关, 图像差分显示半影衰退而本影变得更黑, 认为在耀斑之后大约一小时后磁场从高度倾斜变为更垂直形状, 或者说, 一部分半影磁场转变为本影磁场。

● 运动与机制研究

➤ 沿着磁中性线的光球剪切流动

采用高适应光学系统、框架选择及, 掩饰方法, 分析了 2003 年 10 月 29 日在萨克拉门托峰国家太阳观测站邓恩望远镜观测到的 10486 活动区 X10 级白光耀斑之前两小时的自行运动, 用局部相关跟踪方法测量光球自行运动, 发现了沿磁中性线的强剪切流, 这些剪切流域可见及红外的白光耀斑核相关。

➤ 旋转黑子与耀斑的关系

分析了正极黑子的主轴旋转运动的演化及特性，估计他们注入的螺度积累，同时分析了发生在旋转黑子周边的同源耀斑。重要结论为：i) 在活动区正极性的主轴上存在逆时针旋转运动；ii) 从旋转运动得出的螺度注入与用局部相关跟踪方法得出的量相当；iii) 两个与 CME 相关的同源耀斑的始发与黑子的旋转运动在时间及空间上相关。因此，黑子的旋转运动不仅与从低层大气到日冕的磁能与复杂性转变有关，还对同源耀斑的触发起到了关键作用。

➤ 骨牌效应产生暗条不稳定性

进行了多波段分析发现，该活动区有多个拱，在 X17.2 耀斑前一个暗条发生了部分爆发，该爆发引起了低层大气磁零点处的重联及与其它暗条重叠的日冕磁场张力的减少，结果，这些暗条失去稳定并导致耀斑发生。因此，NOAA 10486 耀斑不能有一个简单的标准模型或爆发模型解释，而是由所谓骨牌效应引起，涉及到一系列不稳定过程触发耀斑。

● CME 特性研究

➤ CME 的三维 MHD 模拟

对 CME 进行了数值模拟。从同一个活动区启动两个 CME，一个比另一个大约早一天，用以限制 28 日更快 CME 的太阳风，第二个 CME 以超过 2500 km/s 的速度通过日冕，驱动一个向前的强激波。他们在由 LASCO C3 产生的图像中清楚地识别出了该激波，从模拟中再现合成白光图像中的激波及其外形，无论在形态上还是亮度上，发现 CME 模型与 LASCO 观测非常一致。说明 CME 形状主要由与周围环境的相互作用决定，而与起始过程关系不大。

● 对地效应

➤ 太阳事件产生的相对论核子与电子

2003 年 10 月 28 日太阳耀斑在地球产生了一个相对论粒子，分析了该事件中高能粒子在太阳上的加速及到地球的传播性质，认为不同从中子观测站数据来看，最早到达的粒子是核子，几分钟之后到达了第一个相对论质子。有两类相对论太阳质子 (RSP): 瞬时的与延迟的，前者引起了一个脉冲增强，后者比前

者晚半小时，两者都是从反太阳方向到达。由米波到千米波 (Wind/WAVES) 射电辐射跟踪的亚相对论电子在太阳西半球面伴随米波射电辐射，距离耀斑活动区很远。他们认为地球处在行星 CME (ICME) 与共转流的交界面上，在这种情形下，高能质子与电子在耀斑区加速，注入到根植于活动区的 ICME 环东边足上，在通过环顶点后从反太阳方向到达地球。而瞬时逃逸的亚相对论电子是在太阳西半球面加速且按照正常的 Parker 螺旋传播。

3.4. 其它

3.4.1. 其它相关参考文献

参见第二章 2.2.2.2.1 怀柔站观测到的三个超级活动区, p.72

参见第二章 2.2.2.2.4 全日面准同时磁浮现, p.错误！未定义书签。

参见第二章 2.2.2.2.7 NOAA10484, 10486 和 10488 活动区的色球物质运动和光球黑子旋转, p.错误！未定义书签。

参见第四章 4.2.4.2.8 利用球面非线性无力场分析 NOAA 10486 和 NOAA 10488 的磁场构型, p.错误！未定义书签。

3.4.2. 观测影像资料

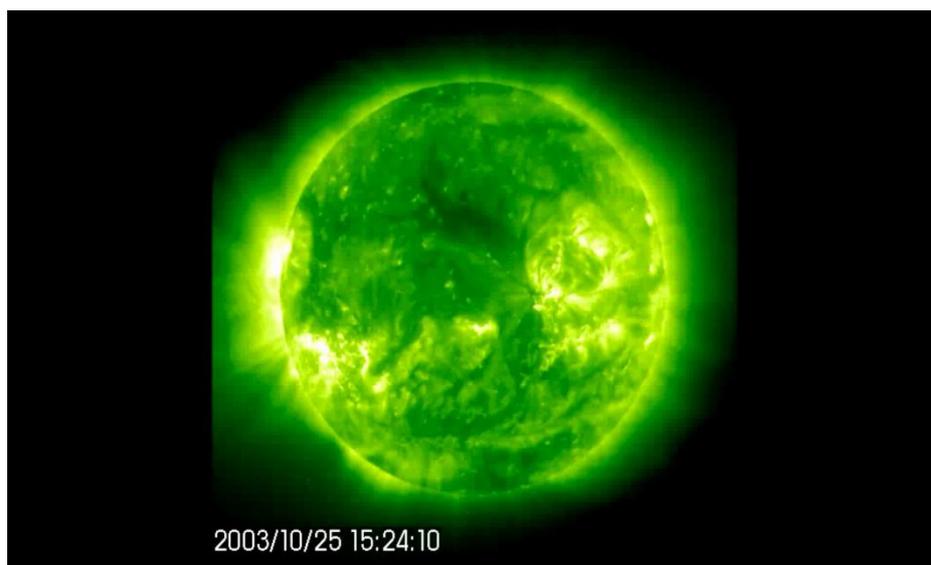


图 3.35: 有史以来记录的[最强耀斑](#)

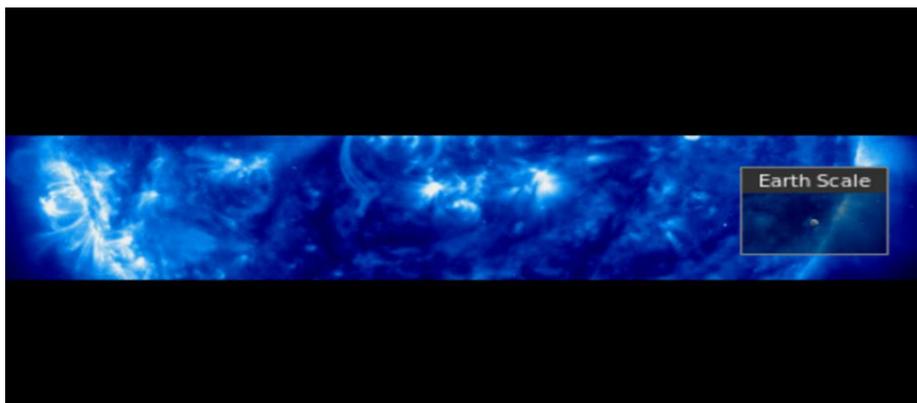


图 3. 36：2003 年 10 月 23 日 01:00:16UT 到 11 月 03 日 19:00:15UT EIT 171A 观测的 NOAA10486 活动区(带状)

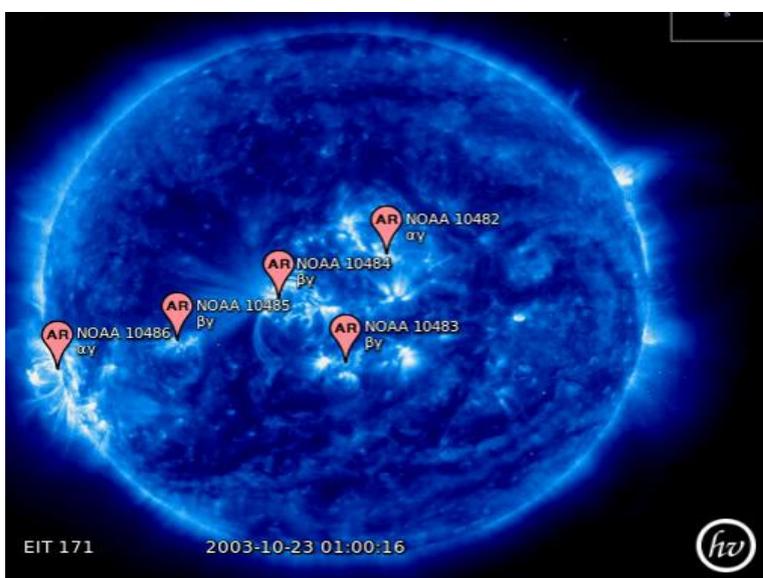


图 3. 37：2003 年 10 月 23 日 01:00:16UT 到 11 月 03 日 19:00:15UT EIT 171A 观测的 NOAA10486 活动区

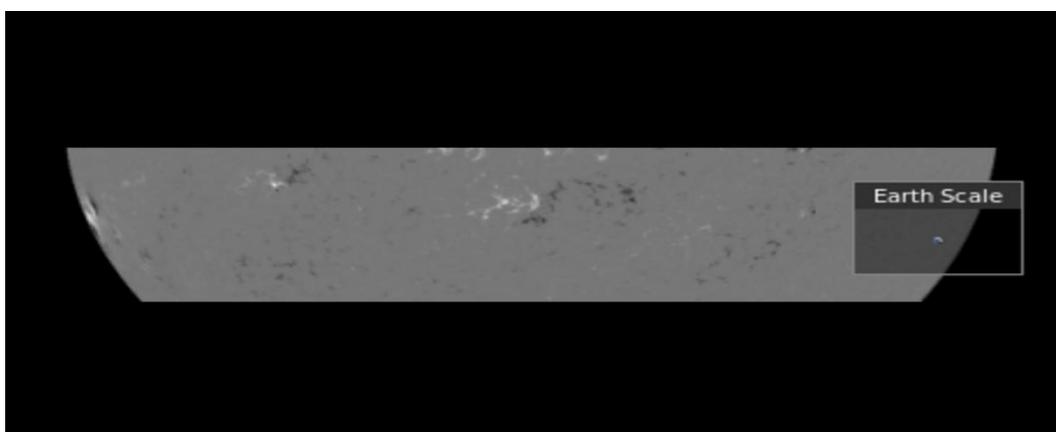


图 3. 38：2003 年 10 月 23 日 01:35:03 到 11 月 03 日 23:59:03UT MDI 磁图(带状)



图 3.39: 2003 年 11 月 4 日 SOHO 观测到的 [X45 巨大太阳耀斑](#)



图 3.40: 2003 年“万圣节”事件 [太阳风暴](#)

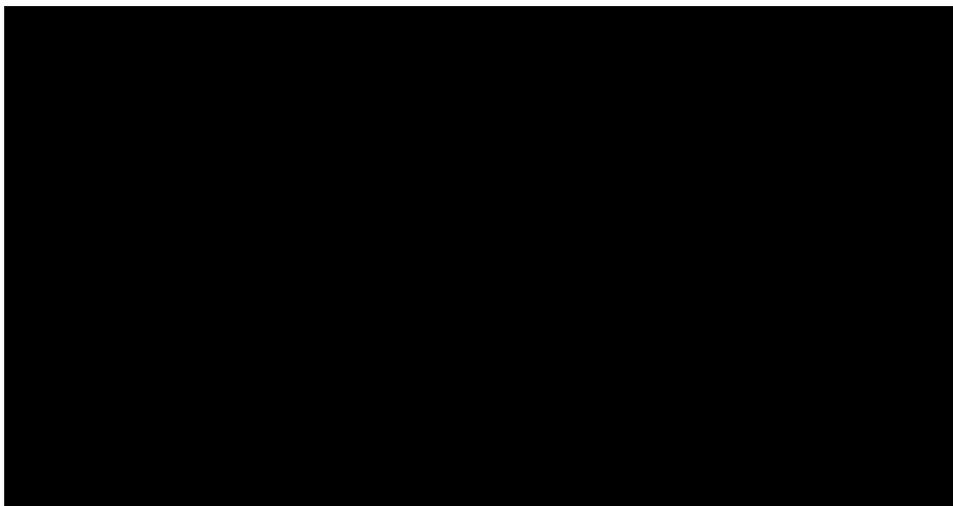


图 3.41: “万圣节”事件 [太阳风暴](#)

3.5. 主要参考文献

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第四章 NOAA10488 活动区（万圣节）事件

4.1. 事件概述

“万圣节事件” NOAA10488 活动区于 2003 年 10 月 27 日在日面中心附近浮现，坐标为 N08W28，11 月 4 日消失在日面西边缘，最初三天快速发展，30 日达到 1750。产生了 3 个 X 级耀斑，7 个 M 级耀斑，17 个 C 级耀斑。

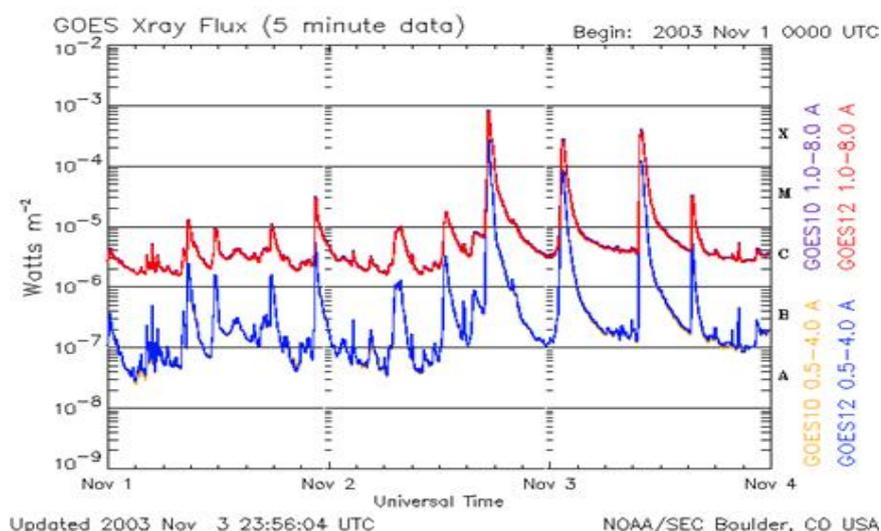


图 4. 1: GOES 卫星软 X 射线流量图(2003 年 11 月 1-3 日)

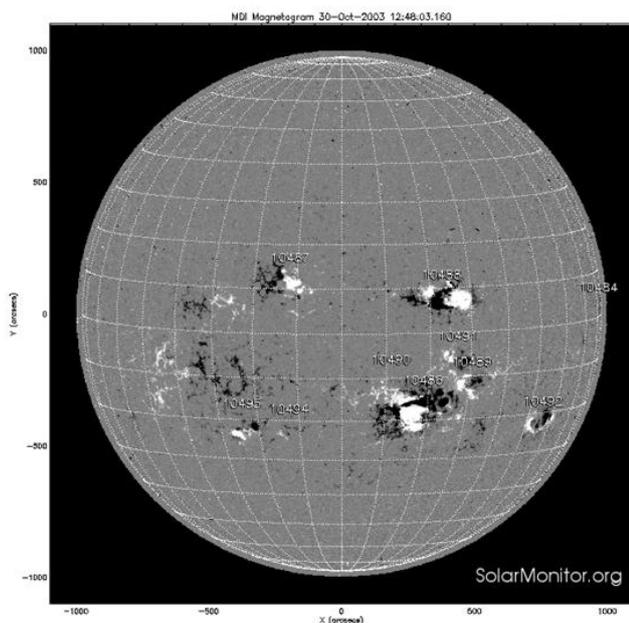


图 4. 2: MDI 全日面磁图

表 4. 1: NOAA10488 活动区观测记录

<i>Region Summary</i>																		
Location		Sunspot Characteristics					Flares											
Date	Helio		Area (10 ⁶ hemi)	Extent (helio)	Spot Class	Spot Count	Mag Class	X-ray			Optical							
	(°Lat °CMD)	Lon						C	M	X	S	1	2	3	4			
<i>Region 488</i>																		
27 Oct	N09E09	292	0270	08	Dko	020	B	3	1	9								
28 Oct	N08W04	291	0800	10	Dkc	034	Bgd	2		16	1							
29 Oct	N07W17	291	1460	16	Fkc	061	Bgd	1		6								
30 Oct	N08W28	289	1750	17	Fkc	034	Bgd	3	1			1						
31 Oct	N08W42	290	1570	17	Fkc	045	Bgd	4	1	8								
01 Nov	N08W55	290	1610	17	Fkc	040	Bgd	4	2	5								
02 Nov	N08W68	290	1600	16	Fkc	023	Bgd		1	1	3							
03 Nov	N08W82	290	1250	19	Fkc	009	Bgd			2	1	2						
04 Nov	N08W95	290	0320	08	Hax	001	A		1									
								17	7	3	48	2	2	0	0			

Crossed West Limb.

Absolute heliographic longitude: 291

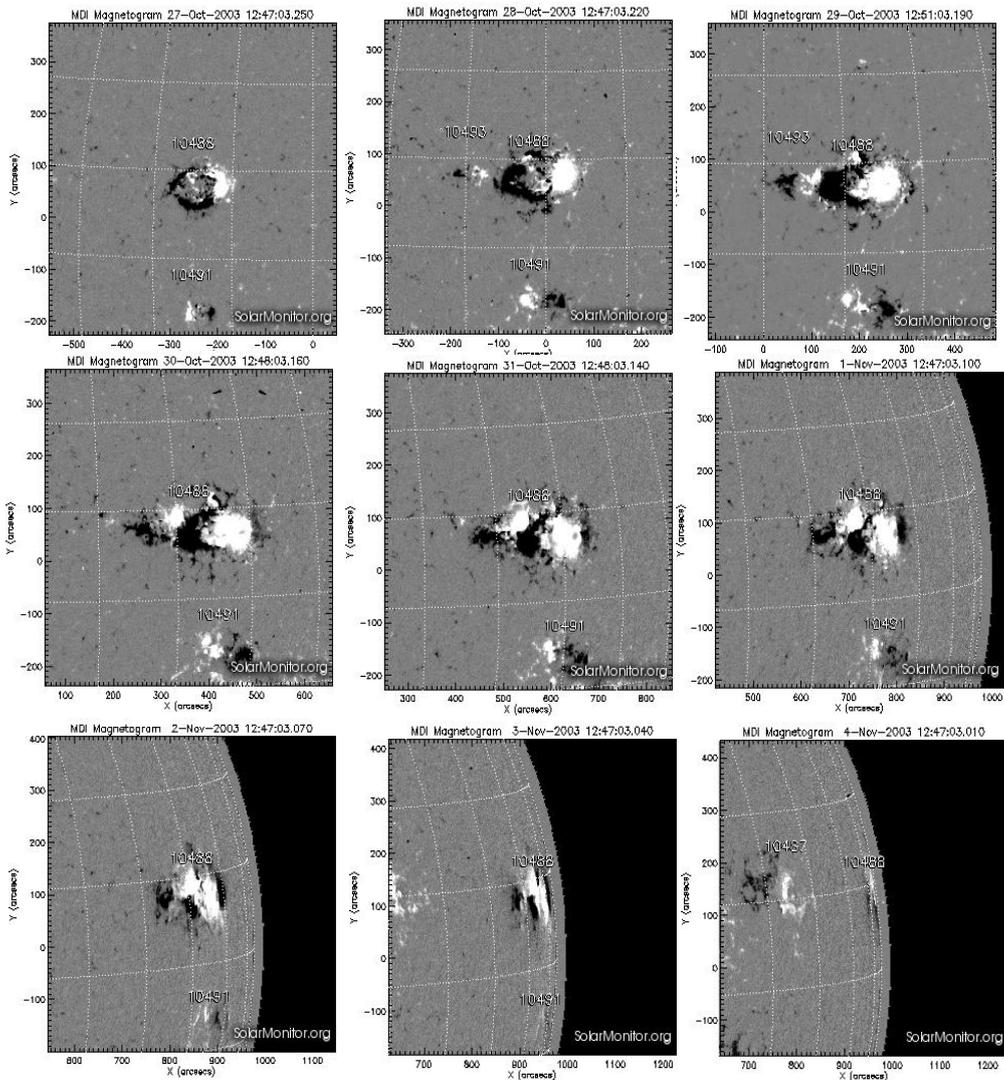


图 4. 3: NOAA10488 活动区日面观测

4.1.1. 事件特征

- 事件观测时间：NOAA10488 活动区于 2003 年 10 月 27 日在日面中心附近浮现，11 月 4 日消失在日面西边缘。
- 最大面积：1750 日面单位；时间：10 月 30 日；位置：N08W28
- 磁位型： $\beta \gamma \delta$
- X 级耀斑数量：3
- M 级耀斑数量：7
- C 级耀斑数量：17
- 最大耀斑级别：X3.9；时间：2003 年 11 月 3 日 09:49UT；位置：N08W77

4.1.2. 观测特征

该活动区在日面中心附近快速浮现发展，强磁场，并快速发展，产生了 3 个 X 级耀斑，7 个 M 级耀斑。

4.2. 相关事件案例研究

NOAA 10488 活动区是“万圣节”事件中等活跃的活动区，活动区在日面中心附近快速浮现发展，产生了多个耀斑，与该事件有关的研究论文有 60 多篇。

4.2.1. 磁螺度研究

刘继红和张洪起（Solar Physics, 2006, 234: 21 - 40）利用怀柔站（HSOS）矢量磁场数据及 MDI 纵向磁场数据，研究了快速上浮 δ 活动区 NOAA 10488 的磁场、运动和螺度，运用局部相关跟踪(LCT)方法来确定磁力线足点的水平拖动速度和磁螺度传输率，发现活动区的上浮可以分为两个阶段：旋转相和剪切相。

光球足点的扭绞形成在活动区上浮的旋转相,而两个磁流系统之间的强剪切行成在接下来的剪切相,强剪切比扭绞带了更多的磁螺度到日冕。在主黑子成熟之后,它的扭绞下降,强剪切变得重要起来并最后成为此活动区的太阳大气中的磁非势性的主要贡献者。所以他们认为在这个活动区与不同磁流系统的链环相关的相互作用与单个磁流系统的扭绞相比可能传输更多的磁螺度到上层大气中去并且对非势性的传输和积累的贡献更大。由水平运动推算出的这个活动区的日冕螺度达到 $-6 \times 10^{43} \text{ Mx}^2$, 他们特别分析了感应电场的纵向分量 E_z , 它的极值约为 $0.1 \sim 0.2 \text{ V cm}^{-1}$, 发现 E_z 的极大值在旋转相位于扭绞区域,在剪切相转移到强剪切区域,这意味着参数 E_z 可能与此活动区太阳大气的非势性有关。然而对于此活动区发生的 M1.6 级的耀斑,没有发现 $H\alpha$ 耀斑核和 E_z 的明显相关。只是在 $H\alpha$ 单色相上强剪切区域有个弱的亮带,对应着强的 E_z 值,这值得进一步研究。这一部分还很好的描述了一个 δ 活动区的形成及其螺度传输。

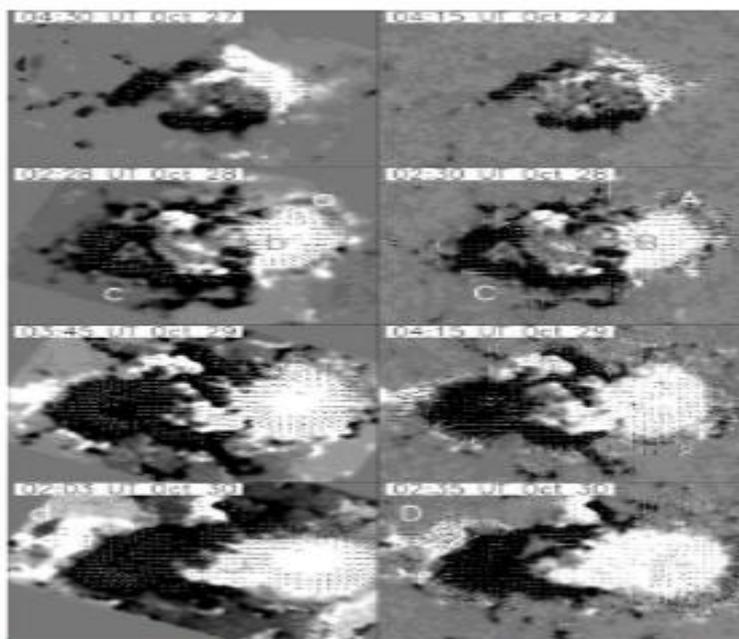


Figure 2. Vector magnetograms of HSOS (left) and computed horizontal velocity vectors being superposed on MDI longitudinal magnetograms (right). The maximum arrow length measures transverse magnetic field of 1200-G and velocity of 0.8 km s^{-1} , respectively. The field of view is $225^\circ \times 168^\circ$.

图 4. 4: NOAA10488 活动区的怀柔站 (HSOS) 矢量磁场 (左), 水平速度叠加在 MDI 的纵向磁场图 (2003 年 10 月 26 日至 11 月 3 日)

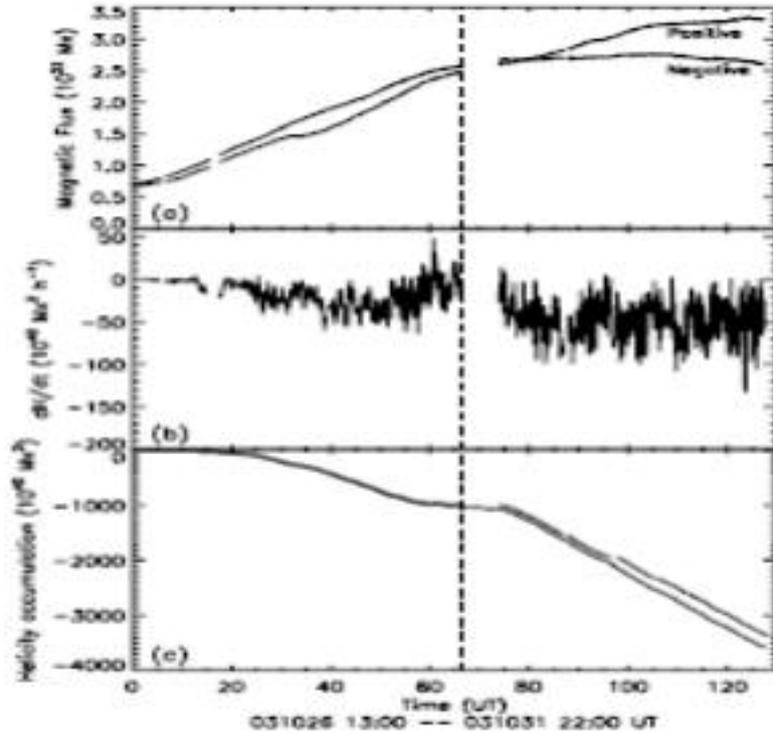


Figure 3. (a) Time profile of the AR's longitudinal magnetic field flux derived from full-disk MDI images. (b) Time profile of the rate of helicity injected by horizontal motions. (c) Time profile of the accumulated change of helicity $\Delta H(t)$ calculated from the measured dH/dt (thick line) and the estimated $\Delta H(t)$ if a spline interpolation is used for the determination of the missing dH/dt values (thin line). The dashed line indicates the time separating the rotation and shear phases.

图 4. 5: 活动区的纵向磁场时间变化 (a), 注入的螺度变化率(b), 及螺度的积累变化(c)

4.2.2. 浮现磁流管在光球层及光球层以下动力学研究

Kosovichev (2009, Space Sci Rev, 144, 175–195) 利用 SOHO/MDI 和 GONG 和观测数据, 分析了在太阳表面和内部观察到的出现磁通量的一些性质, 初步结果显示在磁通量浮现期间的强发散流动, 以及围绕稳定的太阳黑子的局部收敛流动。在新浮现活动区 NOAA 10488 浮现的初始阶段, 活动区中的表面等离子体流的分析显示出强烈的局部上升和下流。发现在通量浮现期间的强发散流动, 以及围绕稳定的太阳黑子的局部收敛流动。在活动区的形成过程中获得的波速图像区域, 表示磁通量集中在刚好在表面下方的强场结构中。

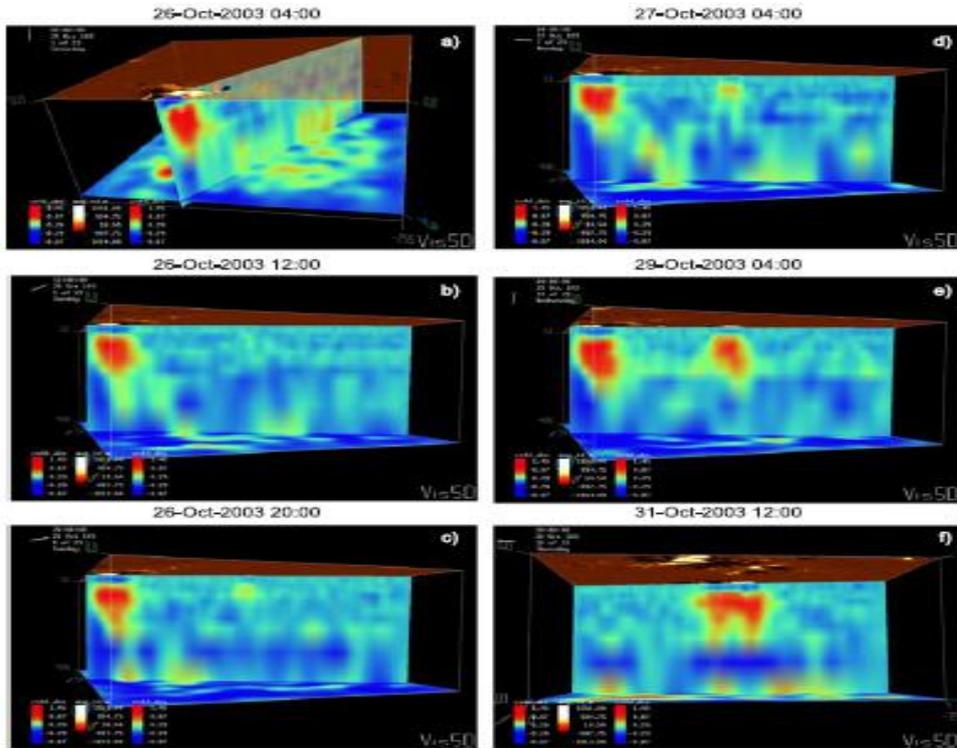


Fig. 10 Subsurface magnetosonic wave-speed structures of the large complex of activity of October–November 2003, consisting of active regions NOAA 10486 (in the *left-hand part* of the images), and 10488 (emerging active region in the middle). *Red color* shows positive wave-speed variations relative to the quiet Sun; the *blue color* shows the negative variations, which are concentrated near the surface. The *upper semi-transparent panels* show the corresponding MDI magnetograms; the *lower panel* is a horizontal cut 48 Mm deep. The horizontal size is about 540 Mm. The vertical cut goes through both active regions, approximately in the North–South direction crossing the equator, except the image in the *right bottom panel*, (f), where it goes only through AR 10488 in the East–West direction

图 4. 6: 活动区 NOAA 10486 和 NOAA 10488 的磁声波速

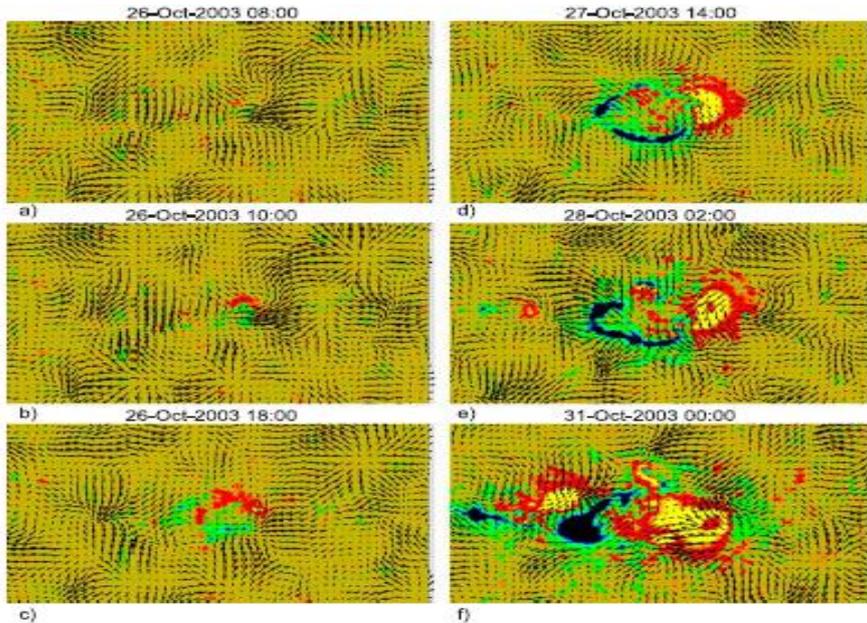


Fig. 12 Evolution of subsurface flows at the depth of 2 Mm below the photosphere during the emergence and growth of AR 10488, on 26–31 October, 2003. The flow maps are obtained by the time–distance technique using 8-hour time series of full-disk Doppler images from SOHO/MDI. The maximum horizontal velocity is approximately 1 km/s. The background image is the corresponding photospheric magnetogram (*red and bright yellow areas* show regions of positive polarity, and *blue* shows negative polarity of the line-of-sight magnetic field)

图 4. 7: 活动区 10488 (2003, 10, 26-31) 光球 2Mm 下流动 (SOHO/MDI)

4.2.3. 在声波能流谱中的表面以下浮现结构信号

Hartlep 等 (2011, Solar Phys, 268, 321–327) 利用 SOHO/MDI 等数据, 通过数据模拟方法讨论了 NOAA10488 活动区的声波传播, 研究了 NOAA10488 浮现之前和期间, 用于测试声功率作为磁通量浮现的潜在前兆的使用。调查了声波功率高于表面以下区域对波速扰动的符号, 深度和强度的依赖性。在该活动区浮现之前, 在 3 到 4 mHz 频率之间声功率减少。

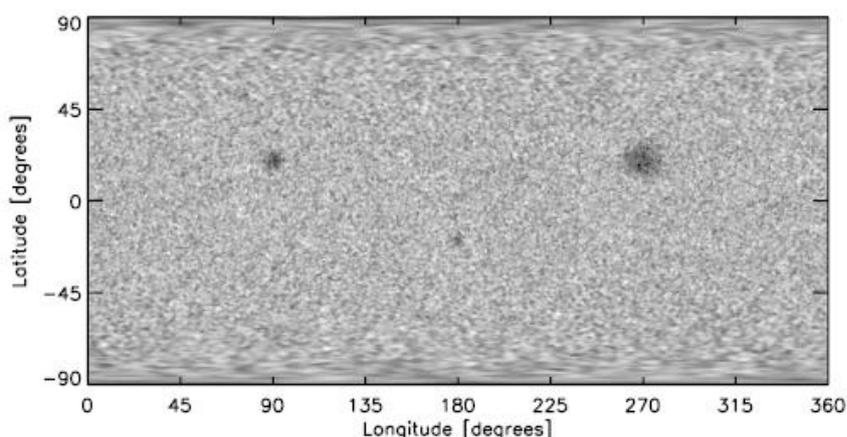


Figure 3 Acoustic power map at 300 km above the photosphere from a simulation with three differently-sized subsurface regions each with a maximum of 10% reduction in sound speed at a depth of 20 Mm. The quantity shown is the square of the radial velocity, averaged over 824 min, with low and high values indicated in dark and bright, respectively. A model subsurface region of 45 Mm radius is located at a latitude of -20° and longitude of 180° . Two larger regions of 90 and 180 Mm radius are located at a latitude of $+20^\circ$, and longitudes of 90° and 270° , respectively. The map has a resolution of approximately 0.703° per pixel both in latitude and longitude.

图 4. 8: 10488 活动区在光球表面以上 300km 处的声能图

Figure 5 Magnetogram during the emergence of NOAA active region 10488 at 350 minutes into the time series. The square outlines indicate the patches used in Figure 4. The central region is the patch where the active region is emerging, and the quiet-Sun patches around were used for comparison.

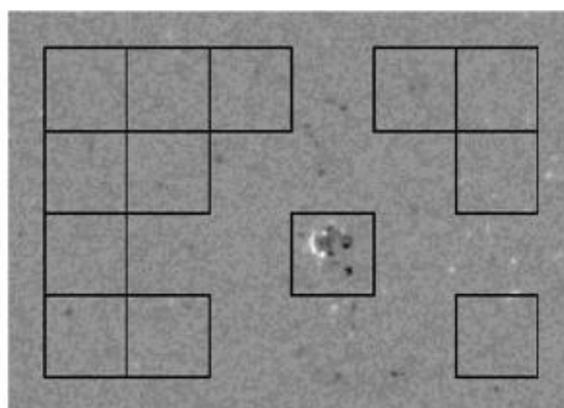


图 4. 9: 10488 活动区的磁图

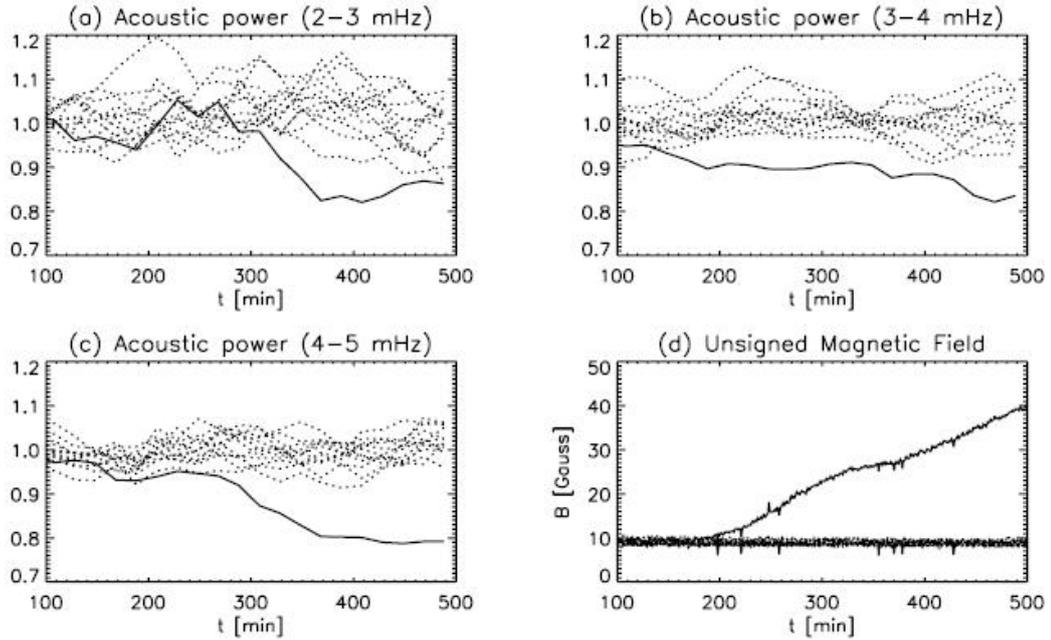


Figure 4 Time series of the observed acoustic power during the emergence of NOAA active region 10488 on 26 October 2003. Shown is, for three different frequency intervals, the power density of Doppler velocities (one-minute cadence) measured in a patch where the active region is emerging (solid line) and in quiet-Sun patches (dotted lines), averaged over the preceding 128 minutes. The values are normalized by the power density at the same disk location but 24 hours later when there was no active region present. This is done in order to reduce the changing projection effects as the active region is tracked across the disk. Except for the splitting into frequency intervals, no filtering was done. The lower-right panel shows the unsigned magnetic field averaged over the same patches to indicate the timeline of emergence. The locations of the selected patches are shown in Figure 5.

图 4.10: 10488 活动区 (2003, 10, 26) 期间观测的声能时间序列, 在 3-4mHz 范围, 活动区发现明显不同

4.2.4. 活动区演化的多尺度分析

Hewett 等 (2008, *Solar Phys*, 248, 311 - 322) 利用 SOHO/MDI 磁图, 使用 2D 连续小波技术来研究活动区 10488 的多尺度结构, 以在 13 天的时间尺度上提取该区域的能谱, 研究发现随着活动区浮现到发展成熟, 能量逐渐从小尺度到大尺度转移, 提供了能量反向级联的证据, 并给出了能量尺度和活动区耀斑发生之间的潜在关系。

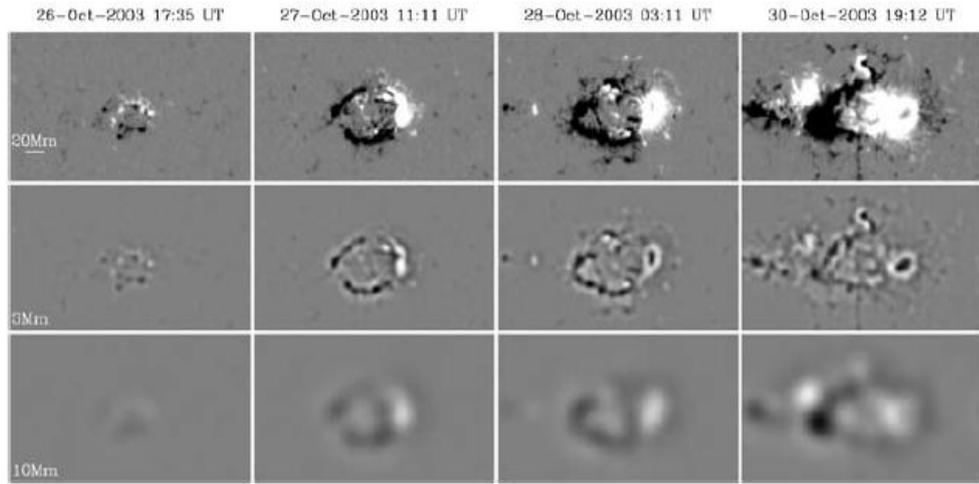


Figure 6 Top row: Calibrated, projection-corrected images of NOAA 10488. Middle row: The wavelet coefficients of these images at a length scale of 3 Mm. Bottom row: The wavelet coefficients of these images at a length scale of 10 Mm. Columns from right to left show the evolution of NOAA 10488 over a four-day time period.

图 4. 11: NOAA10488 活动区磁图及小波系数

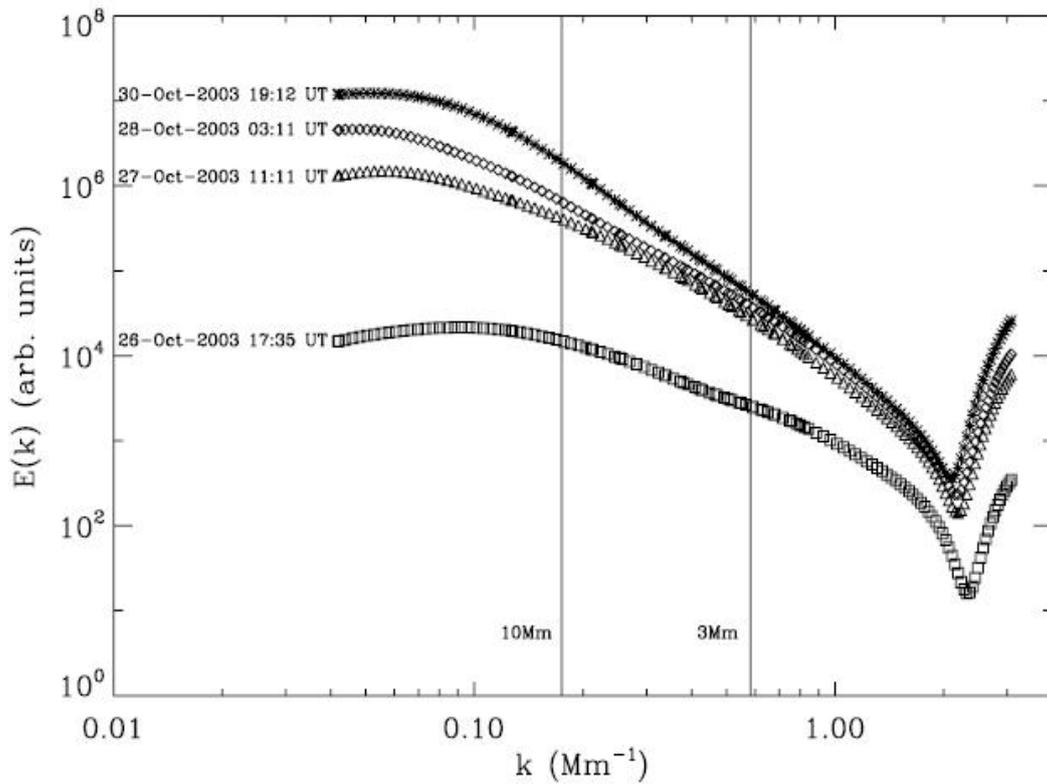


Figure 9 The evolution of the energy spectrum of NOAA 10488 for the four times shown in Figure 6, as a function of spatial frequency. The inertial range is marked with vertical lines.

图 4. 12: NOAA10488 活动区能量谱随频率的演化

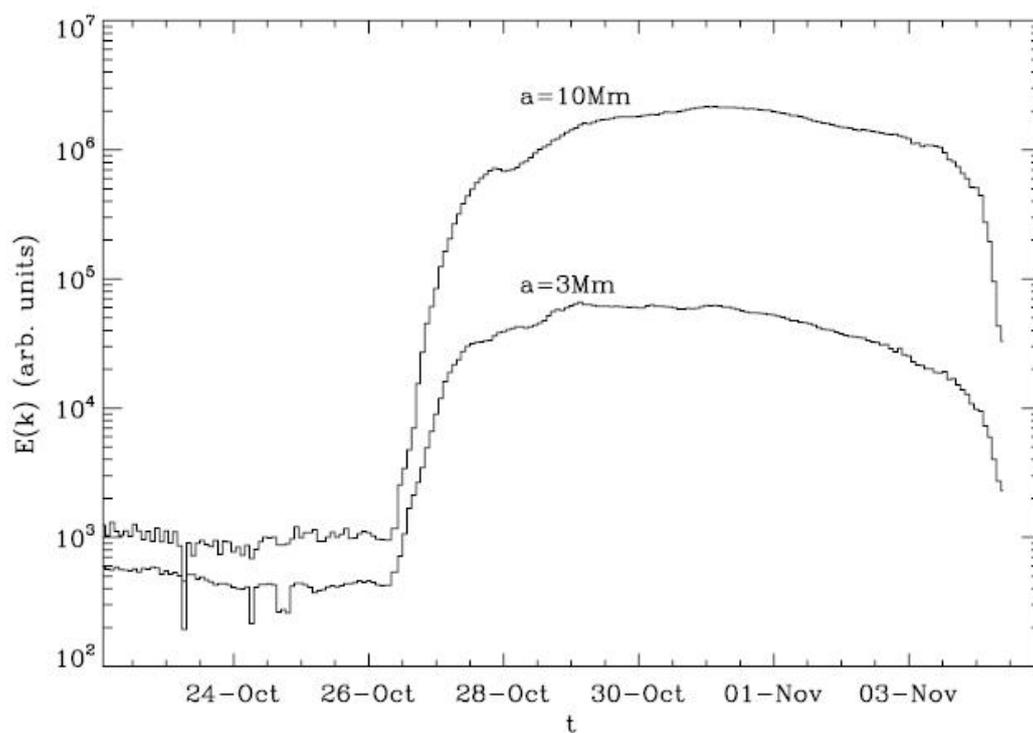


Figure 10 The change in energy of NOAA 10488 in two length scales over two weeks time.

图 4. 13: NOAA10488 活动区能量的时间演化

4.2.5. 用环图（RING-DIAGRAM）方法研究活动区的浮现

Komm 等（2008，APJ, 672, 1254–1265）利用 Global Oscillation Network Group (GONG)数据，使用环图（RING-DIAGRAM）分析导出垂直流分量，研究新浮现活动区域的向下流的时间变化，AR 10488 活动出现之前在深度 4Mm 之内存在较小的向上流，在更深的地方，活动区建立之后存在较强的向下流，从分析的 13 个新浮现地区发现，在新的通量出现之前到通量出现后，有一个上升流朝向向下流的转变。

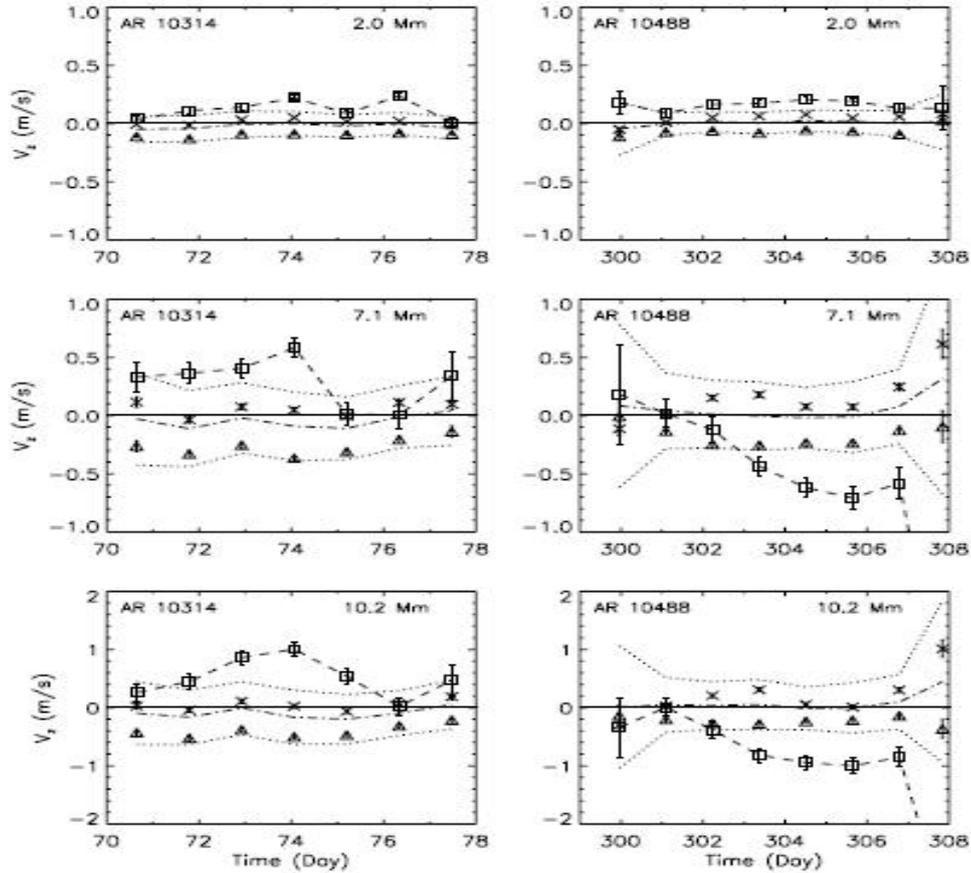


FIG. 5.—Temporal variation of the vertical velocity (squares) at three different depths (top to bottom: 2.0, 7.1, and 10.2 Mm) of A.R. 10314 (left) and A.R. 10488 (right). Positive/negative values indicate up/downflows. The scale is in units of day of year. The dot-dashed line indicates the average temporal variations calculated at the same location as the active regions at 55 Carrington rotations, while the dotted lines indicate the standard deviation. The average variation of the velocities of the lower and upper 25% flux tubes (crosses and triangles) are included for comparison.

图 4. 14: 活动区 10314 (左) 活动 10488 (右) 在不同深度 (2.0, 7.1 和 10.2 Mm) 垂直流的时间演化

表 4. 2: 13 个浮现活动区垂直流情况

TABLE 1
EMERGING ACTIVE REGIONS

AR Number	CR	Longitude	Latitude	Flux	Before	After	Difference
9574.....	1979	165.0	0.0	51	Down	Up	Up
9800.....	1985	60.0	7.5	52	Up	Up	0
9912.....	1988	67.5	7.5	52	Down	Down	Down
10050.....	1992	195.0	-7.5	101	Down	Up	Up
10119.....	1994	232.5	-7.5	57	Up	Down	Down
10226.....	1997	135.0	-30.0	61	0	Up	Up
	1997	135.0	-22.5	60	0	0	0
10314.....	2000	60.0	-15.0	65	Up	Up	Down
10319.....	2001	255.0	15.0	63	0	0	0
10323.....	2001	180.0	-7.5	70	Up	Down	Down
10365.....	2003	225.0	-7.5	80	0	Up	Up
10493.....	2009	285.0	7.5	86	0	Down	Down
10488.....	2009	292.5	7.5	145	0	Down	Down
	2009	292.5	0.0	59	Down	Down	Down
	2009	300.0	7.5	74	0	Up	Up
10564.....	2013	165.0	15.0	92	Up	0	Down
	2013	165.0	7.5	56	Up	Down	Down
	2013	157.5	7.5	55	0	Down	Down

NOTES.—Listed are active region number, Carrington rotation, Carrington longitude and latitude (in dense-pack grid), absolute flux after emergence (in G), direction of vertical flow before and after flux emergence (down, up, or zero within one error bar) averaged over 2–10 Mm. Three regions are located in more than one dense-pack patch; additional locations are appended after the main location.

4.2.6. 活动区 NOAA10488 在形成时光球内的视向速度及磁场动力学行为

Grigorev (2007, *Astronomy Letters*, 33, No. 11, pp. 766 - 770)通过分析 SOHO 纵向磁图和多普勒速度图,发现 NOAA10488 活动区的环形磁通管的顶部形成一个大的区域通过时,在光球内物质存在显著的上升流,最大上升流速度达到 2km 每秒,最大尺度超过 20000km,时间大约 2 小时。

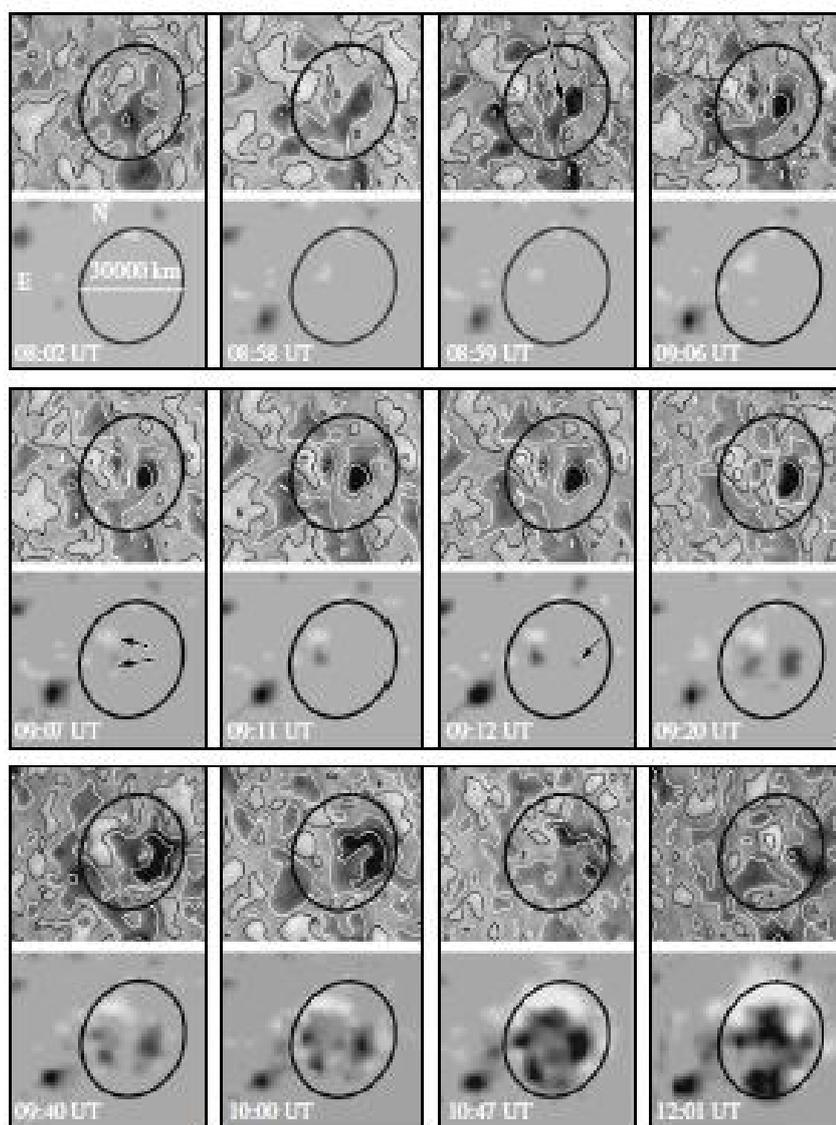


Fig. 2. Maps of the line-of-sight velocity field with ± 100 and ± 400 m s^{-1} isolines and longitudinal magnetograms showing the dynamics of material and magnetic field during the formation of an active region.

图 4. 15: 视向速度及纵向磁图显示活动区在形成时物质及磁场的动力学行为

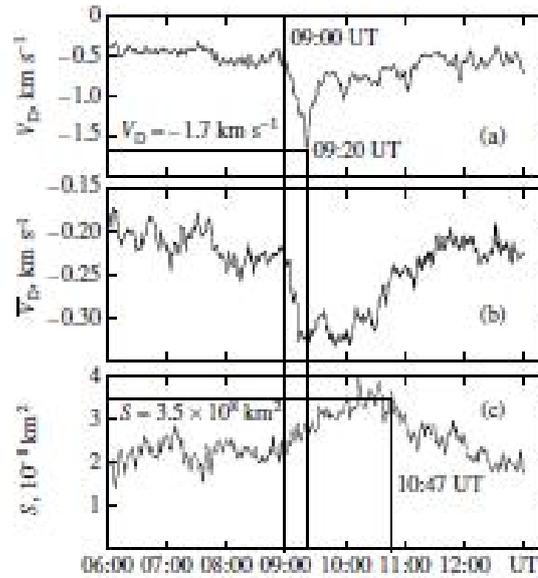


Fig. 3. Timevariations of maximum Doppler velocity V_D (a), mean velocity \bar{V}_D within the contour outlined by the -100 m s^{-1} isoline (b), and area S bounded by the -100 m s^{-1} isoline (c) in the region of magnetic flux emergence.

图 4. 16: 多普勒速度的时间演化

4.2.7. 全日面准同时磁浮现

周桂萍等(2007, *Solar Phys*, 244: 13 - 24)基于全球 $H\alpha$ 和 SOHO / EIT EUV 数据,分析了 2003 年从 10 月下旬到 11 月初出现的一系列强烈的太阳爆发事件,超过六个活动区,包括“万圣节”事件 (NOAA10484, 10486 和 10488) 参与活动,发现非常长的暗条通道通过六个活动区,其中四个明显同时出现磁通量,这意味着这些活动区之间有磁性的连接,在三个主要活动区有相同手征性的磁云。

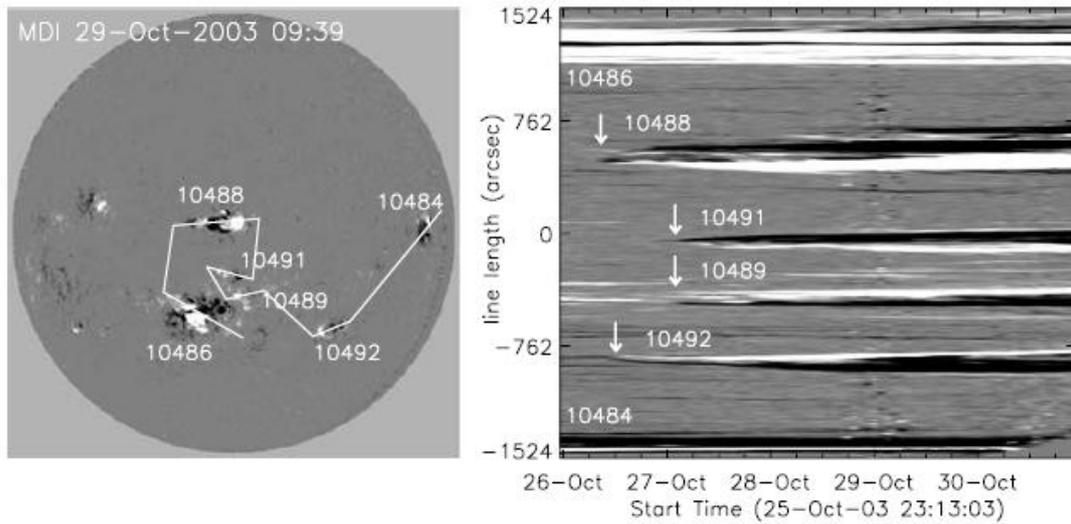


Figure 2 The time evolutions (right panel) of MDI magnetic flux density along a line across the six ARs (left panel). For the line's straight length from right, center, to the left, the positions correspond to -1524 , 0 , and 1524 arcsec, respectively, in the ordinate of the right panel. The MDI flux density evolutions along the line cover the time period from 23:13 UT on 25 October to 22:24 UT on 30 October 2003 with an interval of 96 min.

图 4. 17: 六个活动区 (左) 及沿着跨越其连接线的磁通时间演化

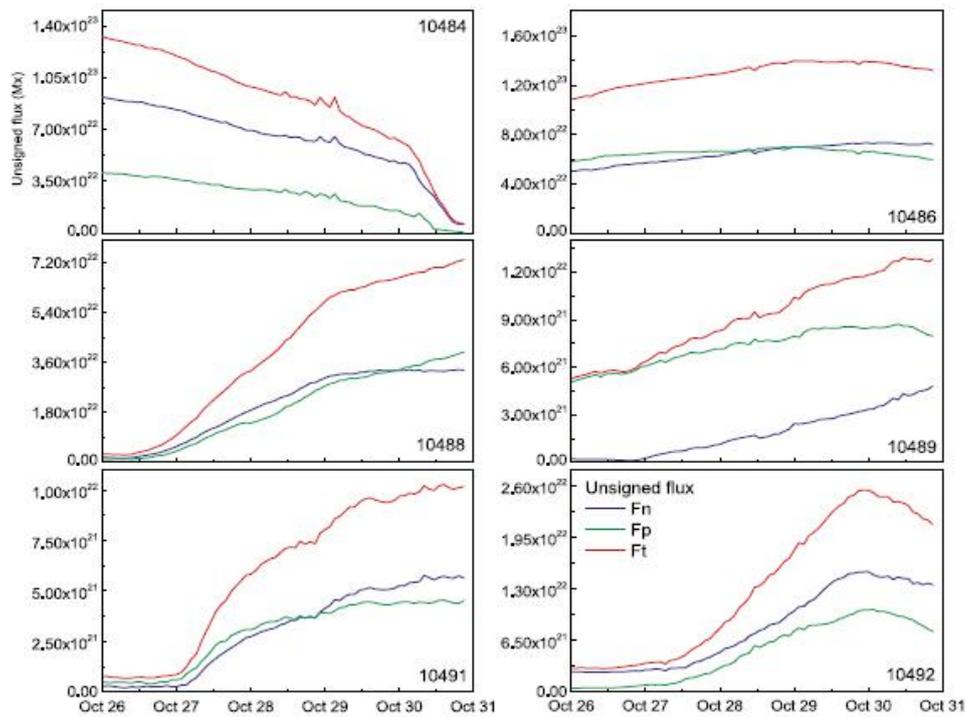


Figure 3 The unsigned emerging flux with time variations in each of the contoured ARs (indicated in Figure 1) shown with positive (F_p , green color), negative (F_n , blue color), and total ($F_t = F_p + F_n$, red color) flux from 23:59 UT on 26 October to 20:48 UT on 30 October.

图 4. 18: 磁通演化

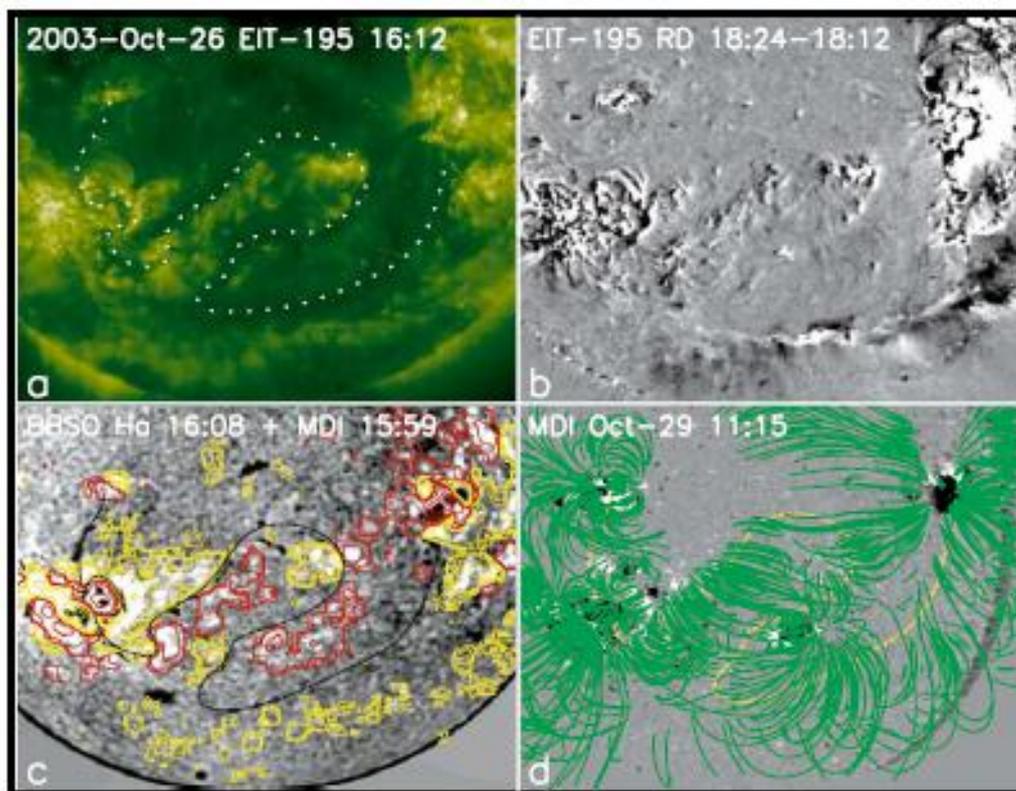


Figure 4 A long filament channel is identified and suggests a connection among the six ARs based on multi-wavelength observations. (a) An EIT 195 Å image at 16:12 UT on 26 October showing the long filament channel as a long narrow dark EUV feature (see the long dotted curve). (b) An EIT running difference (RD) image obtained by subtracting the EUV data at 18:12 from the one at 18:24 UT, which shows coronal dimming along the long filament channel accompanying the associated AR activity. The very long filament channel is situated at a long magnetic neutral line as denoted in panel (c). (c) An H α image at 15:59 on 26 October with contours of nearly simultaneous MDI data. (d) Multiple magnetic arcades overlaying the very long filament channel determined by the method of global potential extrapolation (Wang, Yan, and Wang, 2002). Its background image is an MDI magnetogram at 11:15 UT on 29 October denoting the locations of the six ARs and the long filament channel. The long yellow curve in the figure denote the long filament channel.

图 4. 19: 长暗条通道连接六个活动区。(a) EIT195Å图, (b) EIT 较差图, (c) H α 图像, (d) 与长暗条重叠的多重磁拱

4.2.8. 利用球面非线性无力场分析 NOAA 10486 和 NOAA 10488 的磁场构型

Song 等 (2007, APJ, 666:491Y500) 建立了一种基于光球矢量场的球面非线性无力场 (NFFF) 重建磁图方法, 来了解大规模太阳爆发时的磁场结构, 并分析了在 2003 年 10 月 29 日观察到的两个活性区 NOAA 10486 和 NOAA 10488, 结果表明跨赤道环与极紫外环一致。

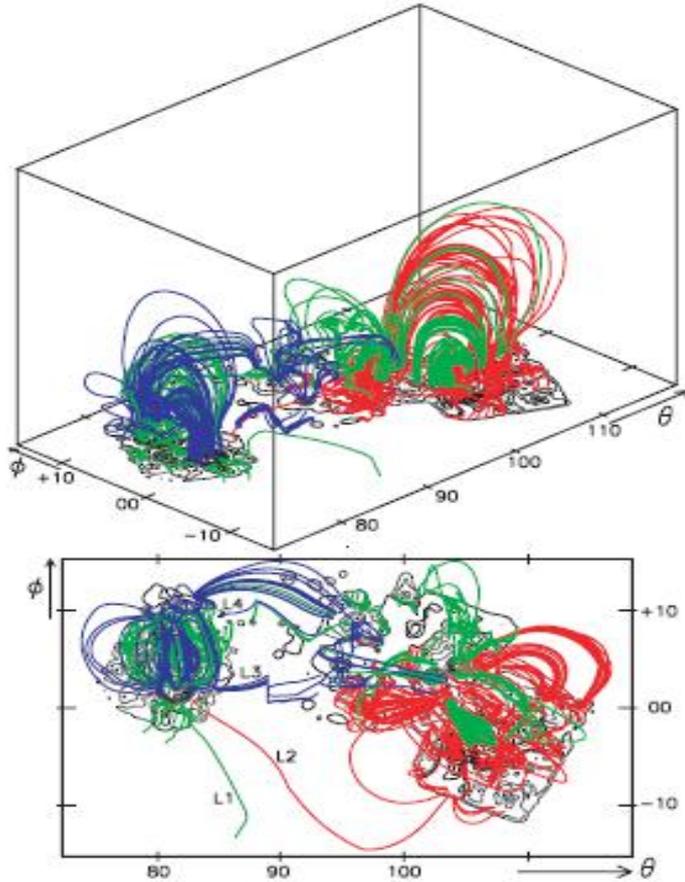


FIG. 6.—Configurations of the NFFF lines computed by use of the vector magnetograms of NOAA 10486 and 10488. *Top*: $\theta_1 = 30^\circ$, $\phi_1 = 225^\circ$, and $I_1 = 60,000$. *Bottom*: $\theta_1 = 0^\circ$, $\phi_1 = 270^\circ$, and $I_1 = 60,000$. The units for θ and ϕ are degrees.

图 4. 20: NOAA 10486 和 10488 活动区的外推磁场构型



FIG. 8.—Computed transequatorial magnetic loops L_1 , L_2 , L_3 , and L_4 superimposed on the EIT image at 03:43 UT on 2003 October 29.

图 4. 21: 计算的跨赤道磁环与 EIT 图比较

4.2.9. NOAA 10488 活动区的中性线相关源分析

中性线相关源 (NLS) 是投影到光球磁场中性线附近的准静止微波源, 经常是强大耀斑的前兆, Uralov 等 (2008, *Solar Phys*, 249, 315–335), 分析 NOAA 10488 日冕中的 NLS 结构及其与能量释放点之间的物理连接。NOAA 10488 活动区磁场演化包括两个双极磁性结构的浮现和碰撞, 主要磁分界的出现以及下面的中性线相关源, NLS 出现在太阳黑子碰撞的接触位置, 随着相对运动导致沿切线的剪切, 然后新生 NLS 成为活动区中微波波动的主要来源。在 17 GHz 的 NLS 发射主要在一个环状结构, 连接两个碰撞的太阳黑子的 NLS 的足点和顶部。在相当长的时间内, 发射主要在 NLS 环足脚点, 那里磁场较强。NLS 类似于通常的太阳黑子相关无线电源, 其亮度中心朝向太阳黑子的周边移位。X2.7 耀斑的微波发射主要集中在上升的耀斑环中, 初始与 NLS 环重合。在耀斑开始, 该环的顶部位于非均匀棒状的底部结构在软 X 射线和 34GHz 中清晰可见。NLS 环的顶部位于该区域的底部。NLS 环和扩散区的组合构成准稳态微波 NLS 的骨架。

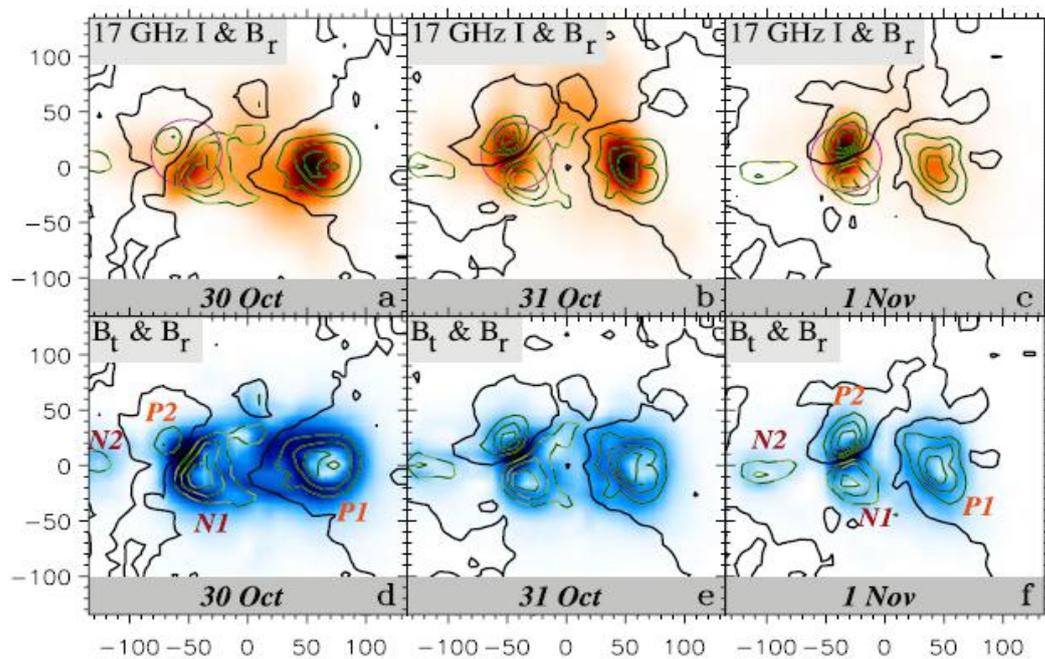


Figure 4 NLS at 17 GHz ((a–c), background) and magnetic components at 2 Mm for three days (same in columns). B_r , green contours in all panels (solid positive, broken negative, thick black the neutral line); $|B_t|$, background in (d–f). Contour levels are $\pm[300, 600, 900]$ G. All frames are centered at Carrington coordinates of $[-68^\circ, 7.2^\circ]$. Axes show arcseconds from the center. Magenta circles in panels (a–c) enclose the birthplace of the NLS, where the horizontal magnetic component $|B_t|$ reaches its maximum. Labels in panels (d, f) denote magnetic sources.

图 4. 22: NOAA 10488 活动区的中性线相关源 (NLS)

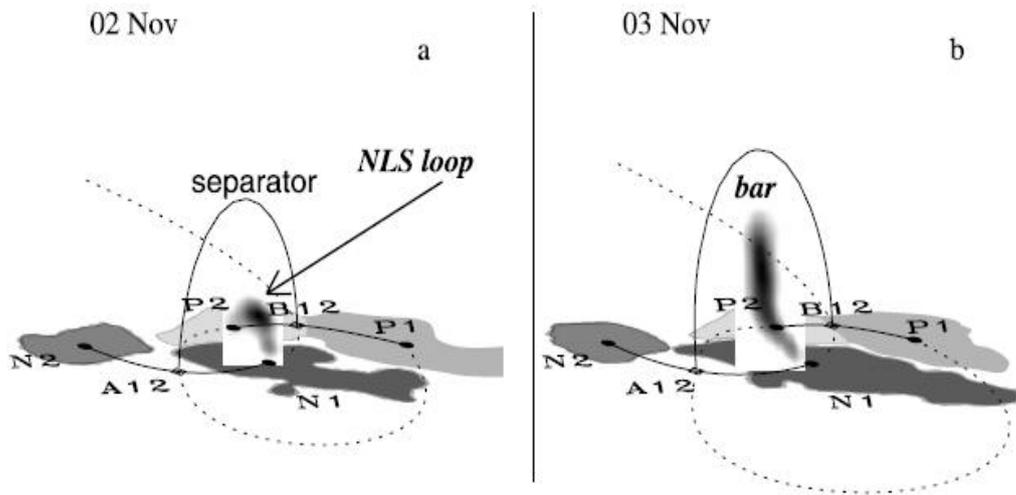


Figure 12 A collage of AR 10488. (a) The NLS loop under the main magnetic separator of the potential-field approach (thick) on 2 November. (b) The bar at 34 GHz under the separator on the next day. The bar is a vertical part of a current sheet before the X2.7 flare. Comparison of (a) and (b) reveals the top of the NLS loop at the bottom of the bar.

图 4. 23: NLS 在势场外推的主磁分割线下 (a) ,34Hz 连接棒第二天在分割线下

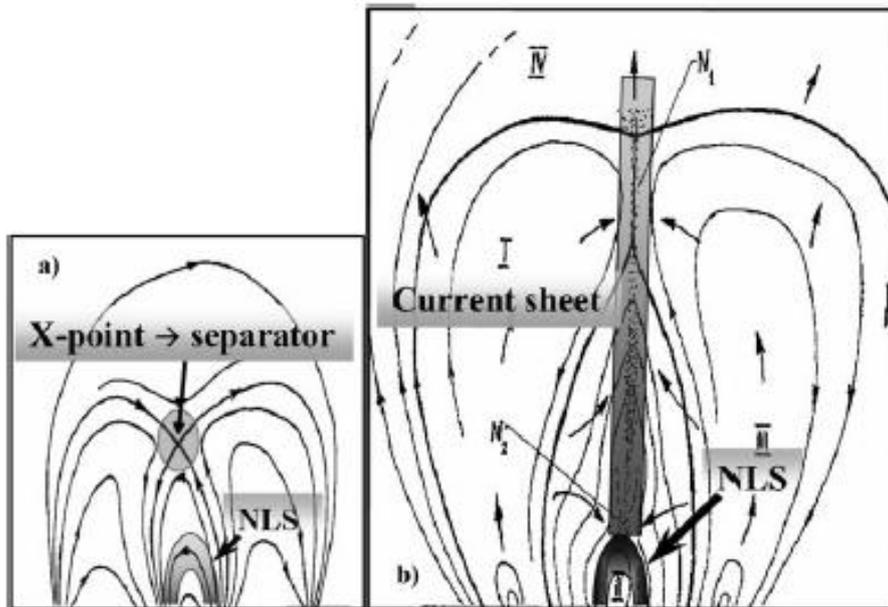


Figure 13 A cartoon of magnetic configurations. (a) A quadrupolar configuration in two dimensions. The position of the NLS loop under an X-point is shown schematically. In three dimensions, the X-point is replaced by a magnetic separator shown in Figure 12. If a current sheet is absent, then plasma parameters in the NLS loop do not differ from the environment, and there is no NLS. (b) Expansion of the magnetosphere of the active region and formation of an extended current sheet (vertical bar). The density of electric current integrated over thickness of the current sheet is maximal not in the vicinity of a potential-approach X-point, but in the lower part of the current sheet. The top of a quasi-stationary NLS loop-like structure is located in its bottom.

图 4. 24: 磁构型卡通图

4.2.10.用日震学方法探测活动区的浅对流区

Toriumi 等 (2013, APJL, 770:L11) 提出了在太阳浅对流区对磁通量上升运动的日震检测, 并给出了浮现速度及其减速性质的估计。为了评估产生活动区的日面以下磁通量的速度, 将六个傅里叶滤波器应用于 NOAA AR 10488 的多普勒数据, 来检测从-15 至-2 Mm 处在六个不同深度处声功率的降低。在磁通量首次浮现在可见表面之前的 2 小时内, 所有过滤的声功率都显示出降低。这些减少的开始时间显示出具有逐渐减速的上升趋势。所获得的速度首先在 15-10Mm 的深度范围内为几公里每秒, 在 10-5Mm 深度处 1.5kms^{-1} , 最后在 5-2Mm 深度处 0.5kms^{-1} 。如果假设功率减小实际上是由磁场引起的, 则 1km s^{-1} 量级的速度很好地符合先前的观测和数值研究。此外, 逐渐减速强烈支持理论模型, 即出现的通量在其扩展到大气中以构建活动区之前在最高对流区域中减慢。

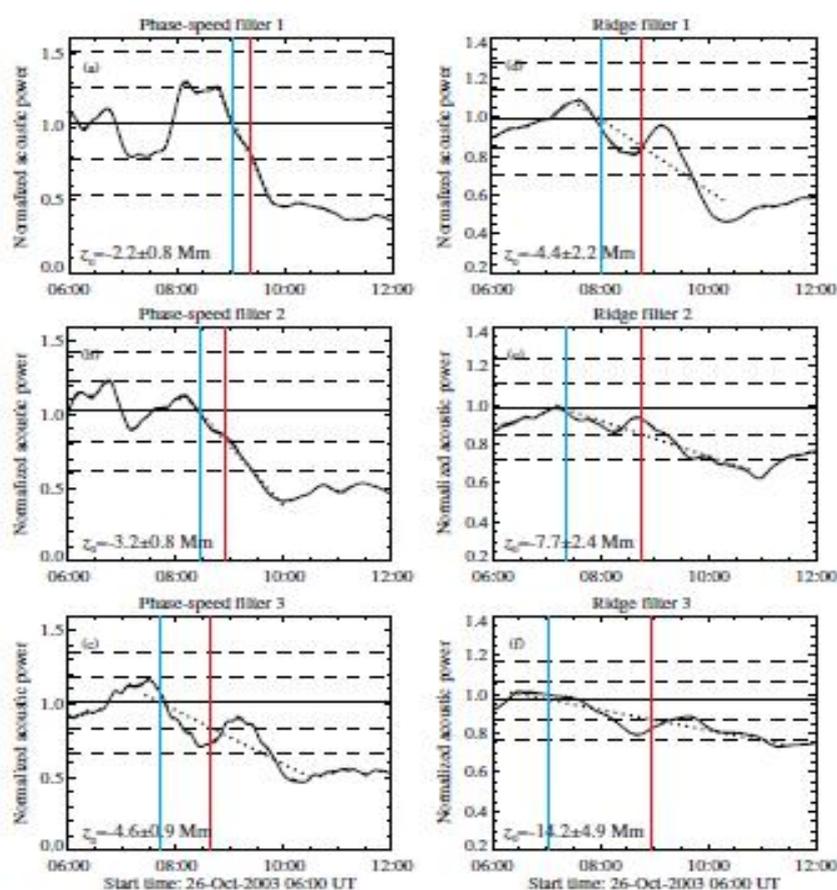


Figure 2. Acoustic power of the emerging AR 10488 normalized by the quiet-Sun power for (a)–(c) phase-speed filters and (d)–(f) ridge filters. The horizontal lines (solid and dashed) are the mean, $\pm 1\sigma$, and $\pm 2\sigma$ power levels calculated from the surrounding region data. The dotted line is a fitted linear trend representing the power reduction, while blue and red vertical lines are the “mean-crossing” and “ -1σ -crossing” times of the dotted line, respectively. The target depth z_0 is indicated in the bottom left of each panel.

(A color version of this figure is available in the online journal.)

图 4.25: 声能变化

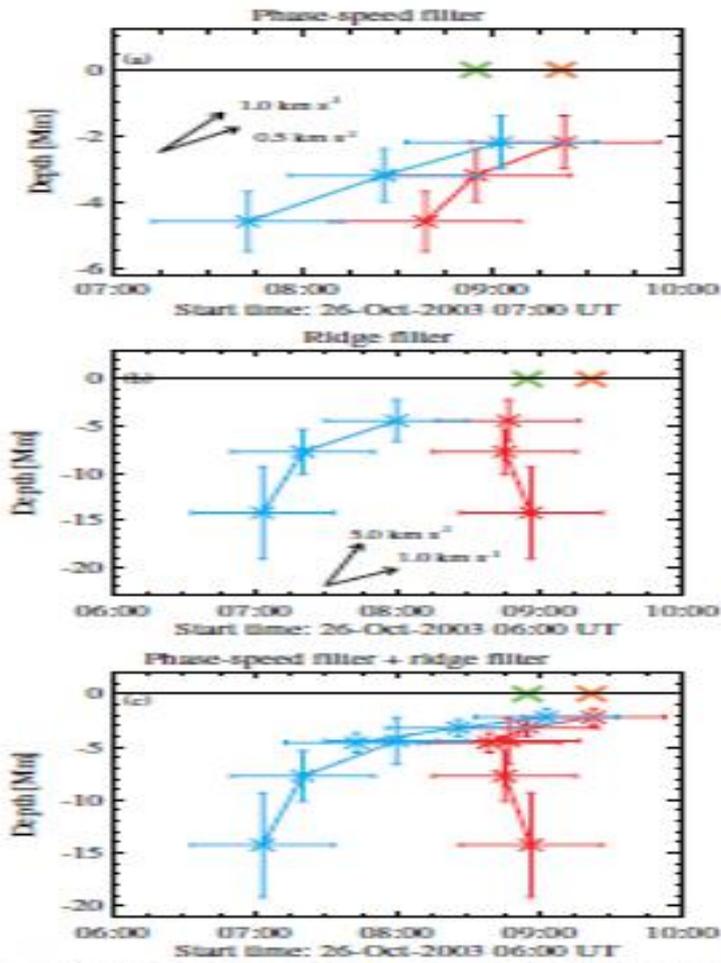


Figure 3. Depth-time evolution of the “mean-crossing” (reduction start, blue) and “ 1σ -crossing” (significant reduction, red) for (a) phase-speed filter, (b) ridge filter, and (c) both. The vertical and horizontal error bars indicate the uncertainty in the effective target depth of each filter and 60 minute smoothing average, respectively. Green and orange X’s are the occurrence time of horizontal divergence flow (TEDF) and the flux appearance measured by the method in Torrance et al. (2002).
(A color version of this figure is available in the online journal.)

图 4. 26: 平均穿越的深度-时间演化

4.2.11. 局部日震学与磁浮现

Kosovichev 和 Duvall (2008, ASP Conference Series, Vol. 383) 用时间-距离日震方法探测了 NOAA10488 活动区的内部信息, 发现在对流区的上端, 磁通传播非常快, 活动区是多重磁通浮现的结果。

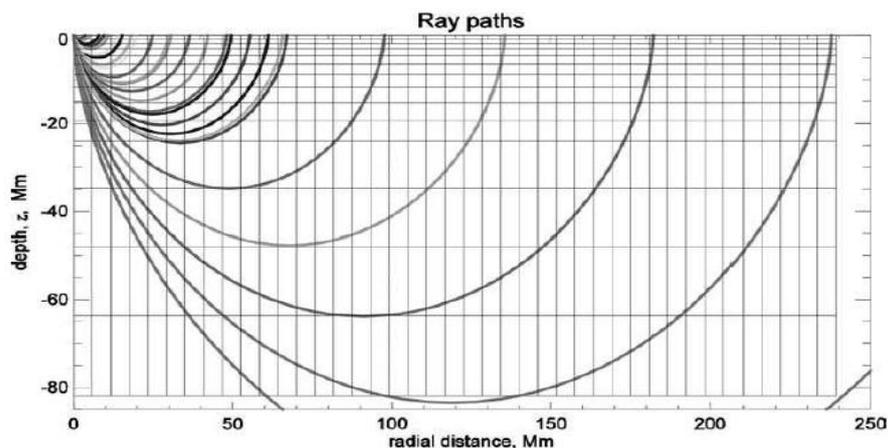


Figure 1. A vertical cut through the computational grid used in the time-distance inversions, and a sample of ray paths of acoustic waves, which were used for measuring travel times.

图 4. 27: 在时间-距离反演方法中用到的计算网格的垂直切片, 及声波传播路径

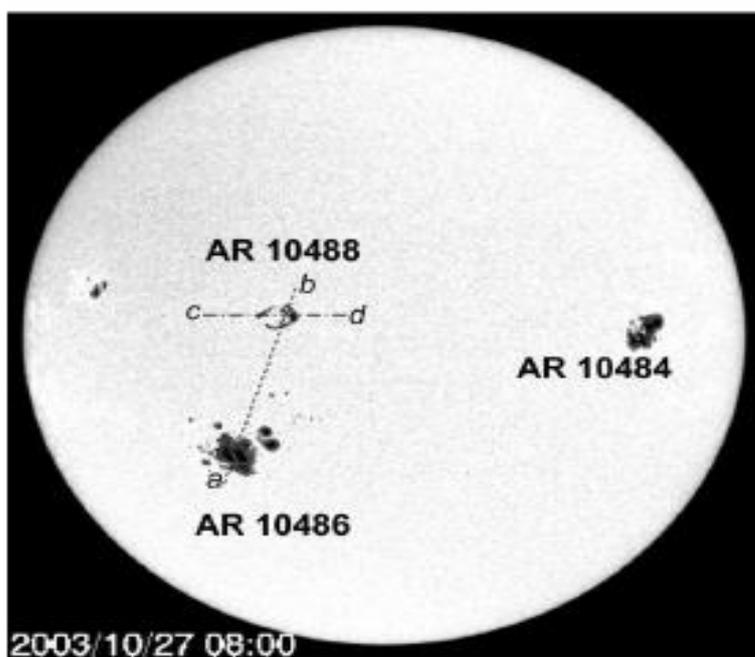


Figure 2. Continuum intensity image from SOHO/MDI, showing the activity complex of NOAA 10486 and 10488, on 27 October, 2003, soon after the emergence of AR 10488. The *a-b* and *c-d* lines show the locations of the vertical cuts of the sound-speed interior images of Figure 3.

(Kosovichev 1996; Couvidat, Birch, & Kosovichev 2006). The sensitivity functions are calculated using a ray theory or more complicated wave perturbation theories, e.g., the Born approximation, which takes into account the finite wavelength effects. These theories can also take into account stochastic properties of acoustic sources distributed over the solar surface (Gizon & Birch 2002; Birch, Kosovichev, & Duvall 2004).

The vertical structure of the computational grid and a sample of acoustic ray paths, used in this paper, are illustrated in Figure 1. The travel times were measured for waves traveling between a central location and surrounding annuli with different radial distances from the central point. The width of the annuli was larger for larger distances in order to improve the signal-to-noise ratio. A set of 17 annuli covering the distance range from 0.54 to 24.06 heliographic degrees (from 6.5 to 292 Mm) was used. The acoustic waves traveling to these distances

图 4. 28: NOAA 10484, 10486 和 104889 (2003 年 10 月 27 日)

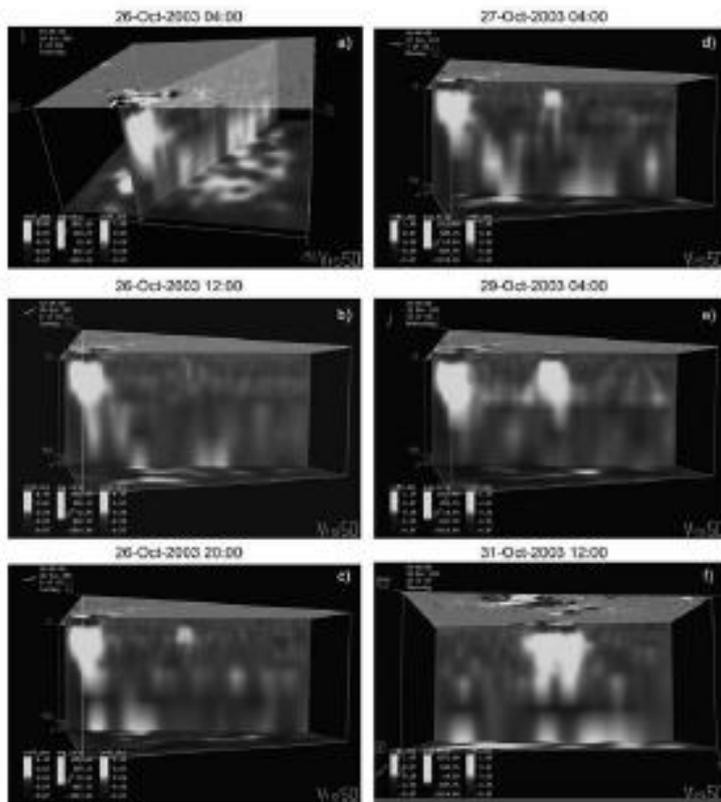


Figure 3. Subsurface sound-speed structures of the large complex of activity of October–November 2003, consisting of active regions NOAA 10486 (in the left-hand part of the images), and 10488 (emerging active region in the middle). Light color shows positive sound-speed variations relative to the quiet Sun; the dark color shows the negative variations, which are concentrated near the surface. The upper semi-transparent panels show the corresponding MDI magnetograms; the lower panel is a horizontal cut 48 Mm deep. The horizontal size is about 540 Mm. The vertical cut goes through both active regions (along the *a-b* dashed line, shown in Figure 2, approximately in the North-South direction, crossing the equator), except the image in the right bottom panel, *f*, where it goes only through AR 10488 in the East-West direction (along the *c-d* line in Fig. 2).

图 4. 29: 包含 10486 和 10488 的表面下声-速结构

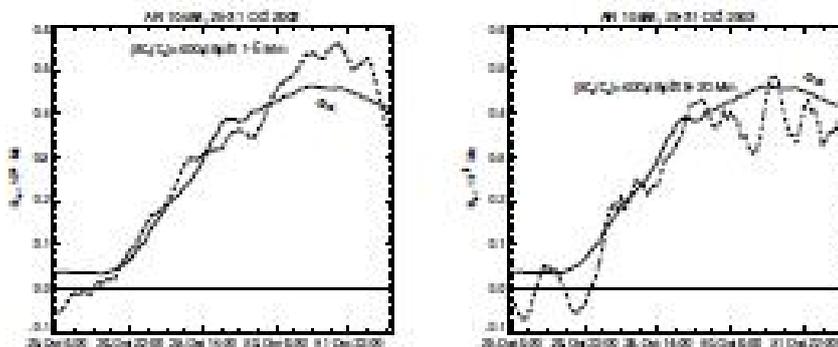


Figure 4. The evolution of the total unsigned photospheric magnetic flux (solid curve) and the mean relative sound-speed variation (dotted curve with stars) at the depth of 1–6 Mm (left) and 8–20 Mm (right) in the region of the flux emergence of AR 10488.

图 4. 30: 10488 活动区的光球磁通演化 (实线) 与平均相对声速变化

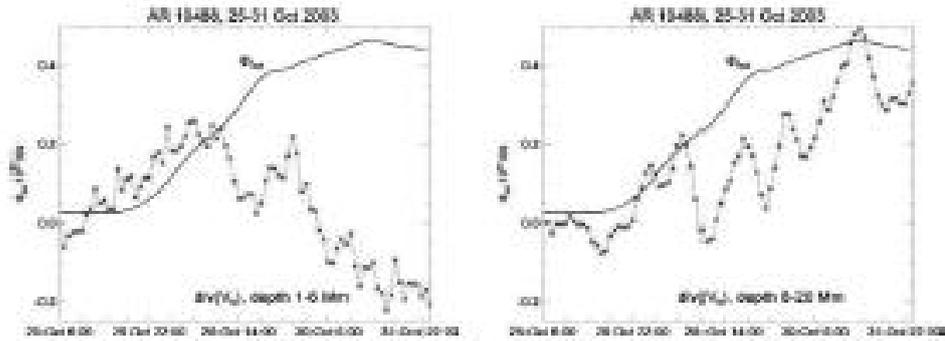


Figure 6. The evolution of the total unsigned photospheric magnetic flux (solid curve) and the mean divergence of the horizontal flow velocity (dotted curve with stars) at the depth of 1-6 Mm (left) and 8-20 Mm (right) in the region of the flux emergence of AR 10488.

图 4. 31: 光球磁通的演化与平均水平流动速度的散度

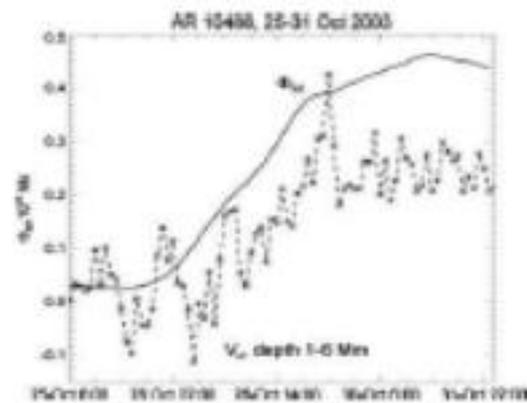


Figure 7. The evolution of the total unsigned photospheric magnetic flux (solid curve) and the mean vertical velocity in km/s (dotted curve with stars) at the depth of 1-6 Mm in the region of the flux emergence of AR 10488. The negative velocity corresponds to upflows, and the positive velocity corresponds to downflows.

图 4. 32: 光球磁通的演化与平均垂直速度

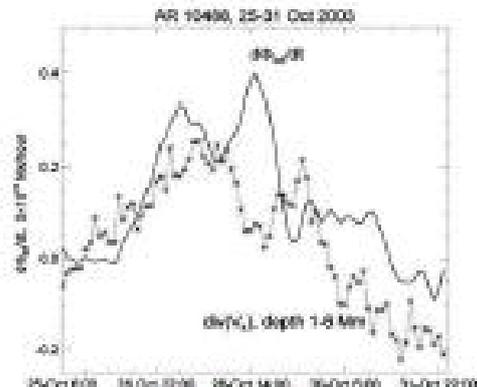


Figure 8. The rate of magnetic flux (solid curve) and the mean divergence of the horizontal flow velocity (dotted curve with stars) at the depth of 1-6 Mm in the region of the flux emergence of AR 10488.

图 4. 33: 光球磁通变化率与平均水平速度的散度

4.2.12.磁零点研究

Zhao 等人 (2005, CHJAA, 5, 443) 研究了 NOAA10488 活动区, 基于 MDI 视向磁场, 采用 Seehafer 提出的常 a 线性无力场外推。在被负磁元环绕的正磁元活动区上方找到一个磁零点。

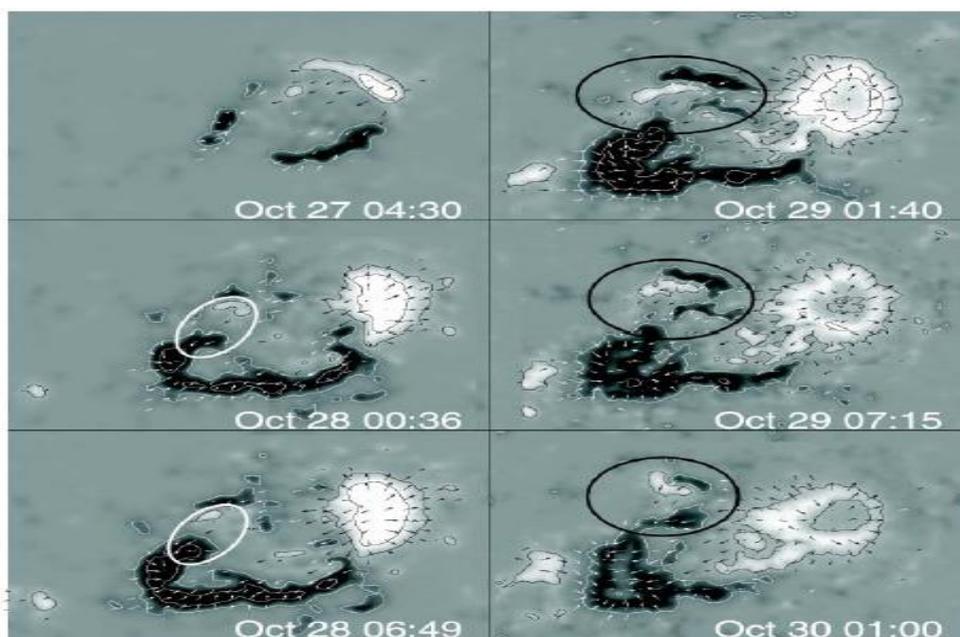


图 4.34; NOAA10488 矢量磁场演化

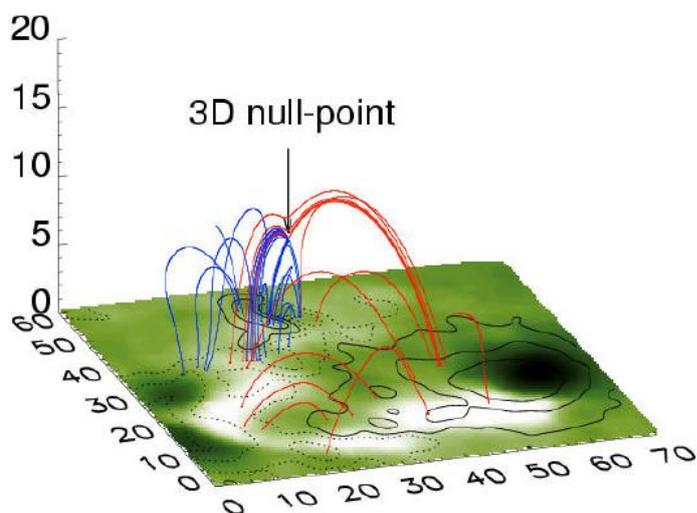


图 4.35: 基于 MDI 纵向磁图外推得到三维磁场中发现一个磁零点。

4.2.13. “万圣节”事件与“巴士底”事件比较研究

Tsurutani 等 (GRL32, L03S09, 2005) 综合比较研究了“万圣节”事件与“巴士底”事件, 2003 年“万圣节”事件中 11 月 4 日耀斑是最大的耀斑(X28)、10 月 28 日耀斑是第四大耀斑(X17), 而 2000 年 7 月 14 日的“巴士底”耀斑级别则为 X10。它们都引起了较强的电离层扰动。

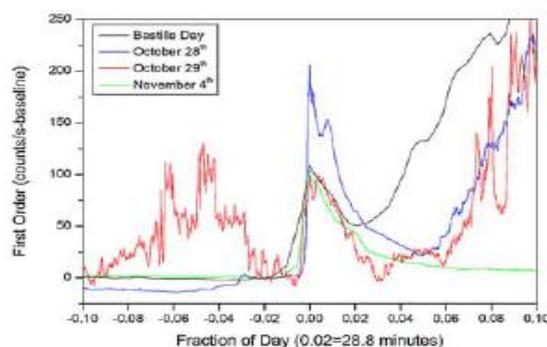


Figure 1. The Oct 28, Oct 29, Nov 4 and Bastille Day solar flare count rates in 26.0–34.0 nm EUV wavelengths. The full disc solar background has been removed from each event. The Oct 28 solar flare is largest by more than a factor of two.

图 4.36 “万圣节”事件与“巴士底”事件比较 (SOHO SEM 26.0 - 34.0 nm (EUV) 计数率)

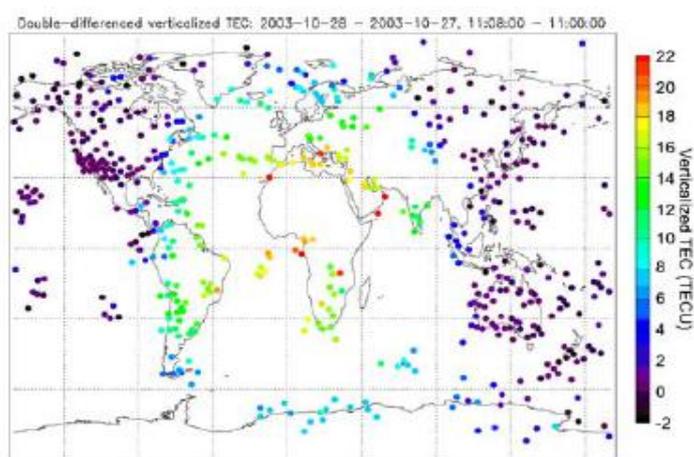


Figure 2. The TEC enhancement for the Oct 28 solar flare. ~100 ground-based GPS receivers were used in this figure. The subsolar point is at the center of the figure, in Africa. The greatest enhancement occurs near the subsolar point and decreases with increasing latitude and longitude away from this point.

图 4.37: 电离层对 10 月 28 日耀斑的响应 (TEC 增强)

4.3. 主要科学贡献

● 螺度传输研究

- 运用局部相关跟踪(LCT)方法来确定磁力线足点的水平拖动速度和磁螺度传输率。
- 研究发现活动区的上浮可以分为两个阶段:旋转相和剪切相。光球足点的扭绞形成在活动区上浮的旋转相,而两个磁流系统之间的强剪切行成在接下来的剪切相。强剪切比扭绞带了更多的磁螺度到日冕。在主黑子成熟之后,它的扭绞下降,强剪切变得重要起来并最后成为此活动区的太阳大气中的磁非势性的主要贡献者。

● 日震学研究

- 浮现磁流管在光球层及光球层以下动力学研究

在大型新浮现活动区 NOAA 10488 浮现的初始阶段,活动区中的表面等离子体流的分析显示出强烈的局部上升和下流。发现在通量浮现期间的强发散流动,以及围绕稳定的太阳黑子的局部收敛流动。在活动区的形成过程中获得的波速图像区域,表示磁通量集中在刚好在表面下方的强场结构中。

- 在声波能流谱中的表面以下浮现结构信号

在某些条件下,太阳表面以下结构,可以改变在其上方光球处观测到的平均声功率(average acoustic power),数值模拟表明这种效应可用于检测将要出现在表面上的新活动区,研究了 NOAA10488 浮现之前和期间,用于测试声功率作为磁通量浮现的潜在前兆的使用。

- 活动区演化的多尺度能谱分析

基于 SOHO/MDI 磁图,使用 2D 连续小波技术测量活动区多尺度结构,以在 13 天的时间尺度上提取活动区能谱。研究发现随着活动区浮现到发展成熟,能量逐渐从小尺度到大尺度转移,提供了能量反向级联的证据,并给出了能量尺度和活动区耀斑发生之间的潜在关系。

➤ 新浮现活动区的表面以下流的时间演化

分析 13 个新浮现活动区发现,在新的通量出现之前到通量出现后,有一个上升流朝向下流的转变。

● 全球太阳活动研究

➤ 全日面准同时磁浮现

从 10 月下旬到 2003 年 11 月初,一系列强烈的太阳爆发事件发生,超过六个活动区,包括三个大活动区 (NOAA 数 10484, 10486 和 10488)。在六个 AR 中,其中四个明显同时出现磁通量基于全球 $H\alpha$ 和 SOHO / EIT EUV 观测,发现非常长的暗条通道通过六个活动区,这意味着这些 AR 之间有磁性的连接。活动区之间的大规模磁连通的观点支持在三个主要活动区相关联的相同手征性的磁云。

➤ 全球非线性无力场

为了了解大规模太阳爆发的起始的物理机制,提出一种基于光球矢量场的球面非线性无力场 (NFFF) 重建磁图。在 2003 年 10 月 29 日观察到的两个活性区 NOAA 10486 和 NOAA 10488,结果表明跨赤道环与极紫外环一致。

● 爆发活动研究

中性线相关源是准固定微波源投影到光球磁场的中性线附近,通常是大耀斑的前兆。分析 NOAA 10488 日冕中的中性线相关源的结构及其与能量释放点之间的物理联系。活动区磁场演化包括两个双极磁性结构的浮现和碰撞。中性线相关源出现在太阳黑子碰撞和强剪切的接触位置,成为活动区中 X2.7 耀斑微波波动的主要来源。

● 磁零点

基于 MDI 视向磁场,采用 Seehafer 提出的常 a 线性无力场外推,在活动区上方找到一个磁零点,磁零点出现在被负磁元环绕的正磁元上方。

4.4. 其它

4.4.1. 其它相关参考文献

参见第二章 2.2.2.2.1 怀柔站观测到的三个超级活动区, p.72

第二章 2.2.2.2.4 全日面准同时磁浮现, p.错误! 未定义书签。

第二章 2.2.2.2.7 NOAA10484, 10486 和 10488 活动区的色球物质运动和光球黑子旋转 p.错误! 未定义书签。

4.4.2. 观测影像资料

参见第三章 3.4.3.4.2 观测影像资料, p. 118

4.5. 主要参考文献

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15. Grigor'ev, V. M., Ermakova, L. V., Khlystova, A. I., Dynamics of magnetic tubes during the formation of a large sunspot, 2012, [Astronomy Reports, 56, 878-886](#)

第五章 NOAA10930 活动区事件

5.1. 事件概述

NOAA10930 活动区于 2006 年 12 月 5 日出现在日面上，2006 年 12 月 18 日消失，产生了 4 个 X 级耀斑（最强 X9.0）、5 个 M 及耀斑，伴随 2006 年 12 月 13 日 X6.5 级耀斑的日冕物质抛射(CME)传播到地球附近，引发强烈的地磁扰动 (Kp=8)。

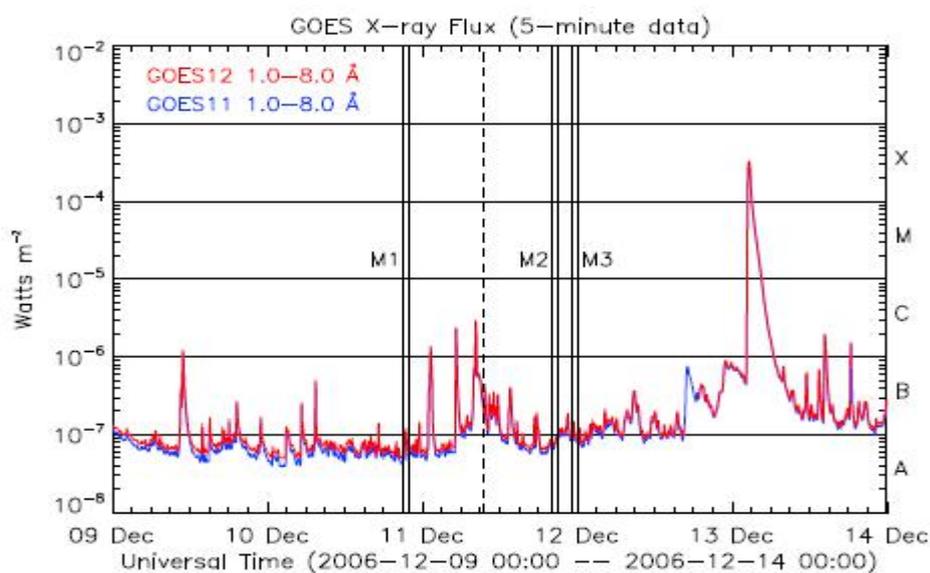


图 5. 1: 2006 年 12 月 9-14 日 GOES 流量及耀斑

表 5. 1: 活动区发生耀斑情况

日期	经度	耀斑	类型	耀斑级别	开始	极大时刻	结束
2006-12-05	-85	M, X 级耀斑	compact	M1.8	0745	0803	0806
			LDE	X9.0	1018	1035	1045
2006-12-06	-72	M, X 级耀斑	LDE	M1.1	0130	0220	0254
			LDE	M6.0	0802	0823	0903
			LDE	X6.5	1829	1847	1900
			compact	M3.5	2014	2019	2022
2006-12-07	-59	M 级耀斑	LDE	M2.0	1820	1913	1933
2006-12-08	-46	无 C 级					
2006-12-09	-33	C 级耀斑					
2006-12-10	-19	无 C 级					
2006-12-11	-6	C 级耀斑					
2006-12-12	+7	无 C 级					
2006-12-13	+20	X 级耀斑	LDE	X3.4	0214	0240	0257
2006-12-14	+33	X 级耀斑	LDE	X1.5	2107	2215	2226
2006-12-15	+46	无 C 级					
2006-12-16	+59	无 C 级					
2006-12-17	+73	C 级耀斑					
2006-12-18	+86	无 C 级					

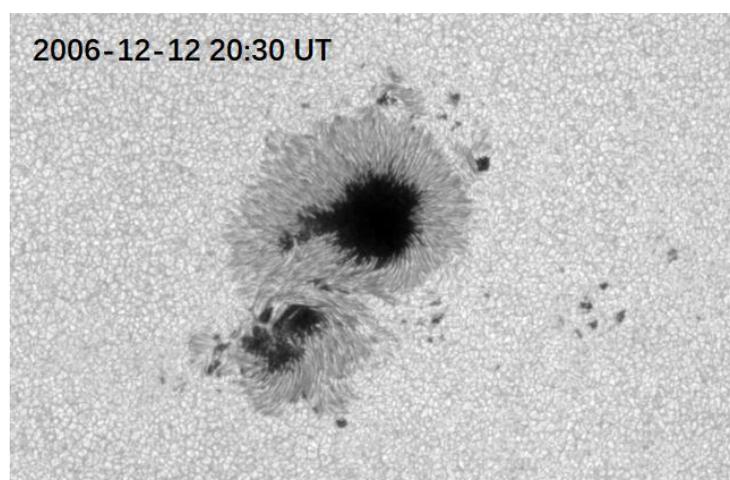


图 5. 2: 2006 年 12 月 12 日 20:30UT 黑子图

5.1.1. 事件特征

- 事件观测时间：2006 年 12 月 5 日到 2006 年 12 月 18 日。
- 最大面积：680 日面单位，时间：2006 年 12 月 13 日；位置：S06W21
- 磁位型： $\beta \gamma \delta$
- X 级耀斑数量：4
- M 级耀斑数量：5
- 最大耀斑级别：X9.0 级；时间：2006 年 12 月 5 日 10:35 UT；位置：S07E68
- 高能粒子事件：4
- CME 事件：3 个全晕 CME
- 对地效应：强烈地磁扰动 $K_p=8$, $Dst=-146$ (12 月 15 日)

5.1.2. 观测特征

NOAA10930 事件期间产生了 4 个 X 级耀斑、4 个高能粒子事件。

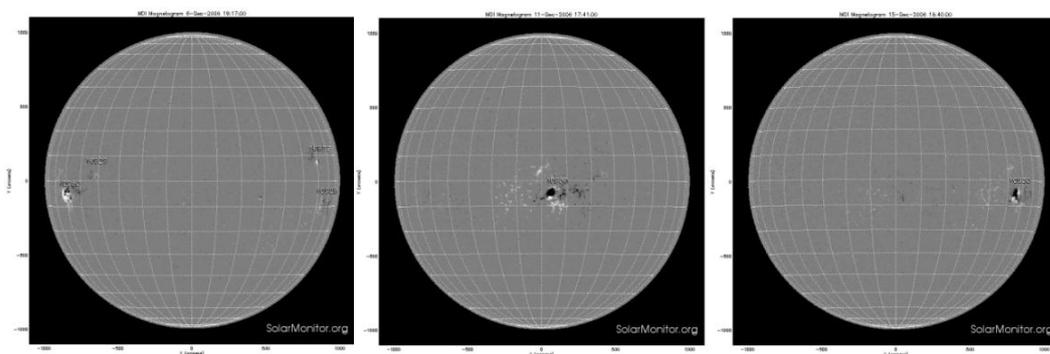


图 5.3：MDI 观测的 NOAA10930 活动区磁图

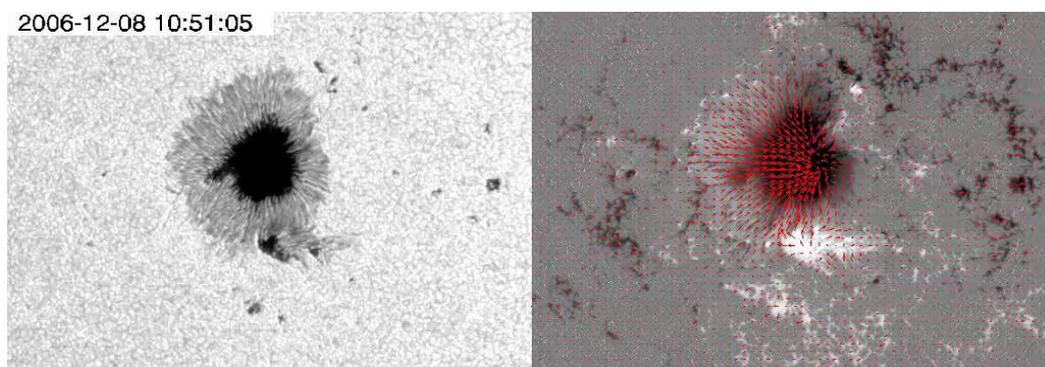


图 5.4：活动区矢量磁图演化(Hinode/SP), 来自 Kubo et al., 2007, PASJ, 59, S779

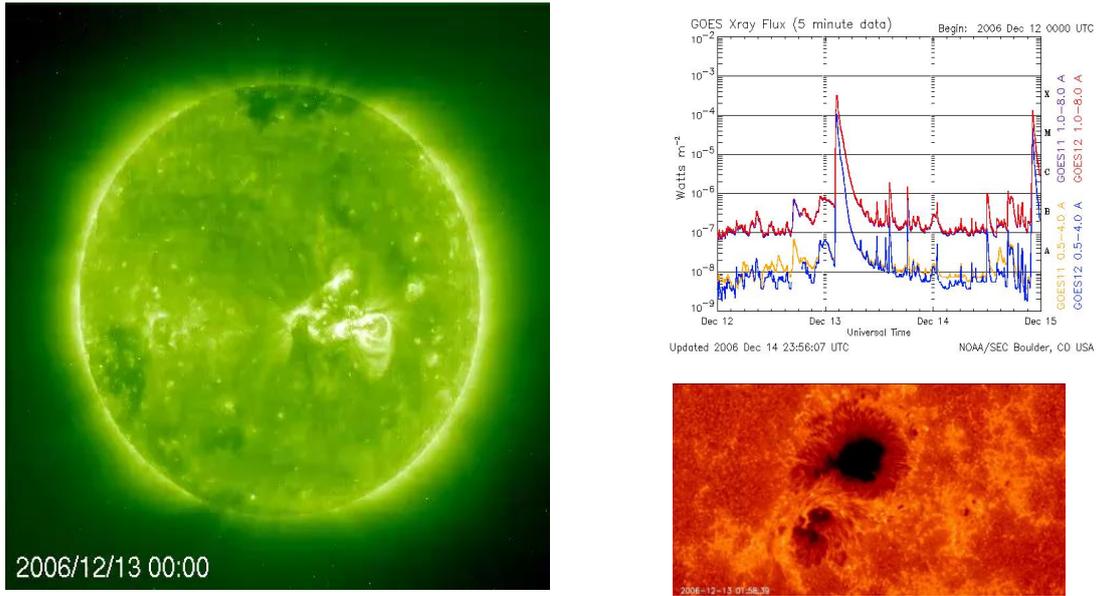


图 5. 5：2006-12-13 观测到的 X3.4 级耀斑（LDE，0214 0240 0257）：左：EUV 19.5 nm 观测 (SOHO/EIT)、右：Call H 396.85nm 观测 (Hinode/SOT)

5.2. 相关事件案例研究

NOAA10930 活动区 2006 年 12 月 5 日出现日面东边缘，2006 年 12 月 18 日消失在日面西边缘，磁位型为 $\beta\gamma\delta$ ，产生了 4 个 X 级耀斑、5 个 M 及耀斑。与该事件有关的研究论文有 100 多篇。

5.2.1. 非线性无力场磁场外推与电流

Schrijver 等 (2008, ApJ, 675, 1637) 利用 Hinode 卫星太阳光球望远镜(SOT)的矢量磁场数据，用 14 种非线性无力场磁场外推 (NLFFF) 模型对 NOAA 10930 活动区进行了分析讨论，指出：(1) 在耀斑之前强电流与磁图同时出现；(2) 这些电流出现在薄层集合中；(3) 这些电流和场线的整体结构与大规模缠绕磁绳拓扑共处；(4) 与冕电流相关的能量变化 (10^{32}erg) 足以激发耀斑及相关的 CME。

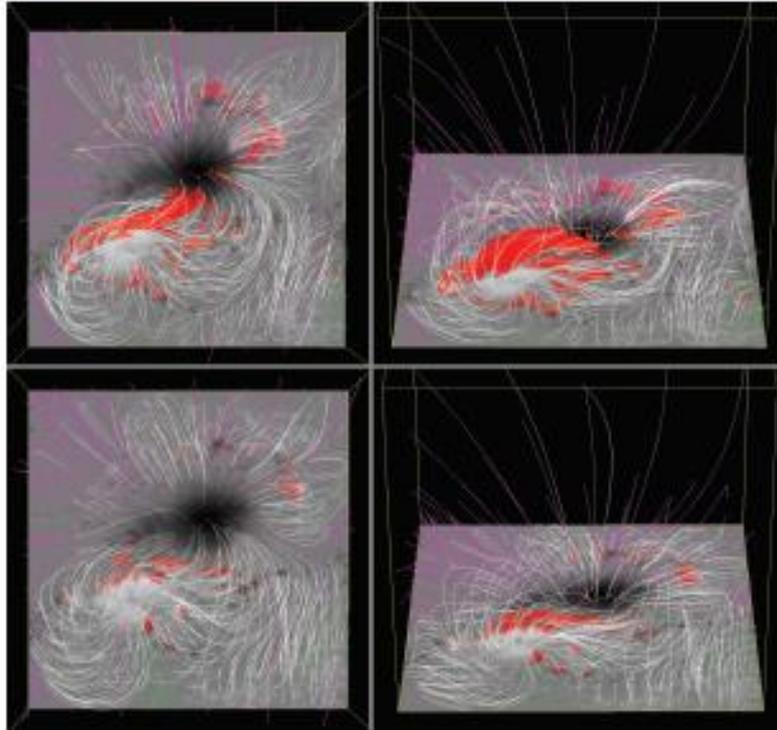


Fig. 3.—Visualizations of the magnetic field over NOAA AIL 10930 before (top) and after (bottom) the X3.4 flare, shown against the corresponding map of S_{\odot} . Sample field lines outline the field; white field lines close within the NLFFF model volume, while colored field lines (purple or green for the two polarities of S_{\odot} , at their base) leave that volume to connect to more distant regions. The rendered volumes (red) show where the electrical current densities are highest, using the same threshold level in both panels (cf. Fig. 2c). The low-lying, compact current system below the large, high-arching currents in the top panel corresponds to the site (position A in Fig. 2d) of the initial high-velocity jets of the X3.4 flare and associated coronal mass ejection. The electronic edition of the *Astrophysical Journal* omits the model results that do not fit as well to the observations as the solutions here.

图 5. 6: NOAA 10930 活动区出现前 (左) 及后 (右) NLFFF 磁场外推

Inoue 等 (2012, APJ, 747, 65) 利用非线性无力场方法分析了 NOAA10930 耀斑, 认为 X 射线强度对电流强度比对场线缠绕更敏感, 即使缠绕较弱, 电流也较强, 而活动区外, 缠绕较强, 电流较弱。

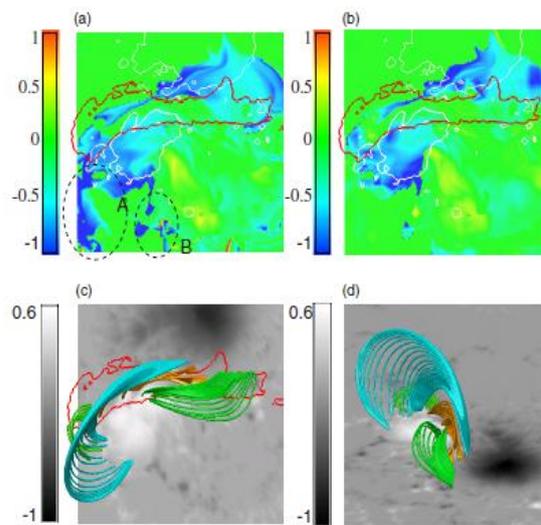


Figure 4. (a) and (b) show a photospheric map of the twist of the field line defined by the second and third terms of Equation (7). Positive and negative values represent the right- and left-handed twist of the field lines. The red contour indicates the X-ray intensity level of 6.8. (c) Magnetic field lines in different colors are plotted over the normal component of the magnetic field (gray-scale image). These colors indicate the different twist values; the orange, green, and blue represent $0 < |T_{\theta}| < 0.25$, $0.25 < |T_{\theta}| < 0.5$, and $0.5 < |T_{\theta}|$, respectively. (d) A side view of (c).

图 5. 7: 缠绕与线场

5.2.2. 非线性无力场磁场外推与剪切

Guo 等 (2008, ApJ, 679, 1629) 使用 Hinode 卫星太阳光球望远镜(SOT)的矢量磁场数据, 对 NOAA 10930 活动区进行了非线性无力场磁场外推 (NLFFF), 结果显示, 从拓扑看表示为一个高度剪切的核场和准势包罗的拱场, 核场显示一些坑来维持暗条, 耀斑后自由能减小。

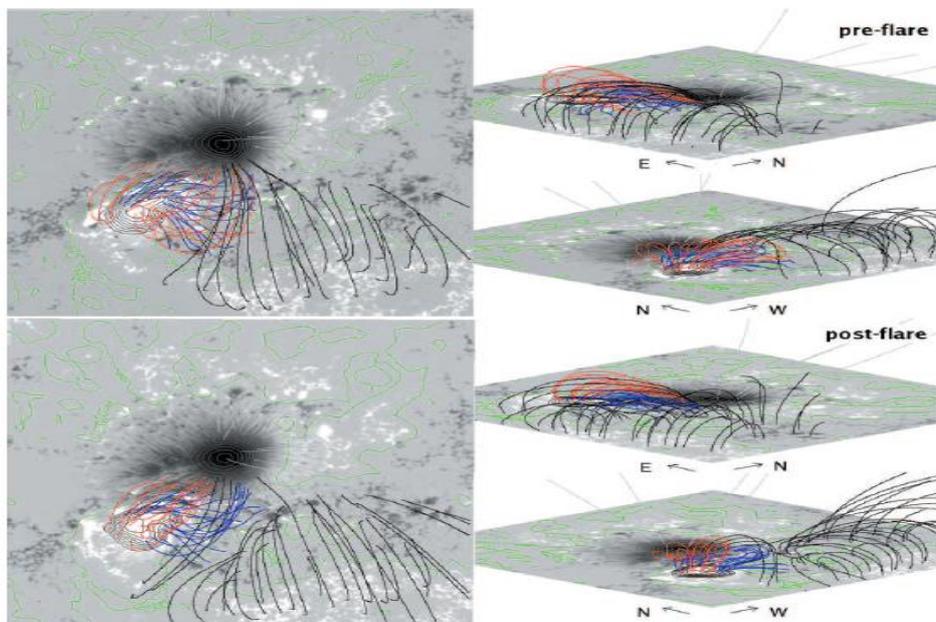


FIG. 2.— Extrapolated 3D magnetic field at a preflare time (*top row*; 20:45–21:15 UT, 2006 December 12) and a postflare time (*bottom row*; 04:45–05:15 UT, 2006 December 13). The left images are for top view, while the right images are for side view with different angles. The gray-scale images correspond to the line-of-sight field overlaid with contour levels. The polarity inversion line is denoted by the green color. See text for details about the field lines.

图 5. 8: 耀斑前后 3D 磁场外推

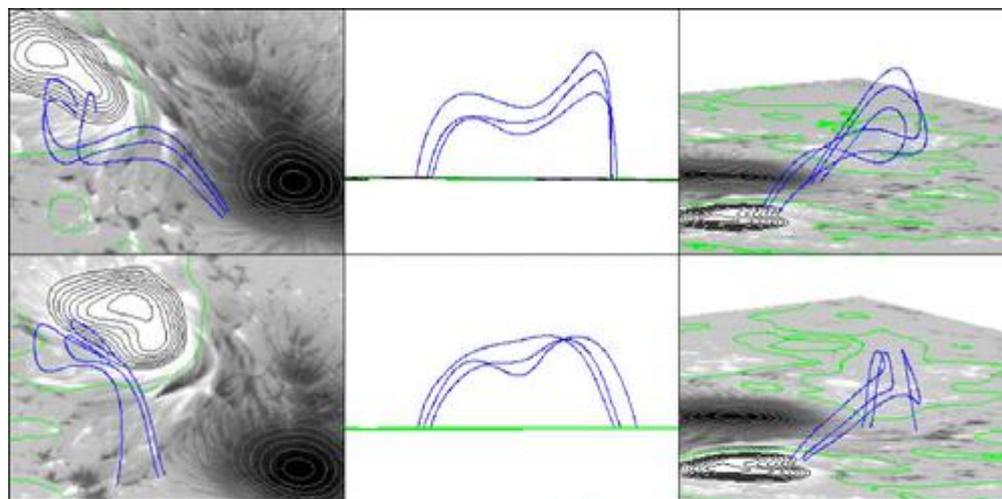


图 5. 9: 在耀斑前(上)后(下)核场的磁力线显示坑

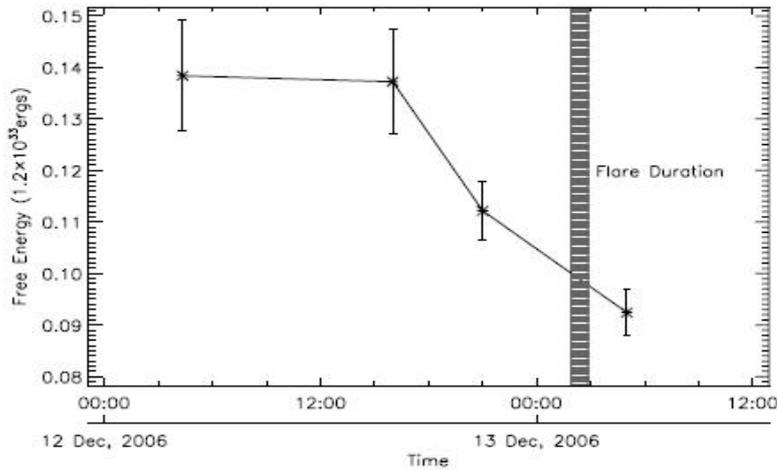


FIG. 4.—Temporal change of free energy in the NLFFF. The flare time is denoted by a vertical bar. The plotted free magnetic energy is normalized by the energy of the potential field before the flare (1.2×10^{33} ergs). The error bars show the uncertainties of the free energies.

图 5. 10: 耀斑前后自由能的变化

5.2.3. 活动区磁场 Twist 和连结性分析

Inoue et al., (2011, ApJ, 738, 161)使用 Hinode/SOT 的矢量磁场数据, 利用非线性无力场磁场外推(NLFFF)讨论了 NOAA 10930 活动区磁场缠绕(Twist), 显示: 1) NLFFF 构造的磁力线足点对应高剪切耀斑带的共轭对; 2) 在耀斑早期, 随着耀斑带远离磁极翻转线, 根植于耀斑带的磁力线缠绕增加; 3) 在耀斑开始前的一天内, 磁通缠绕了半圈多, 且逐渐增加, 而在耀斑后的两小时内, 迅速减小。

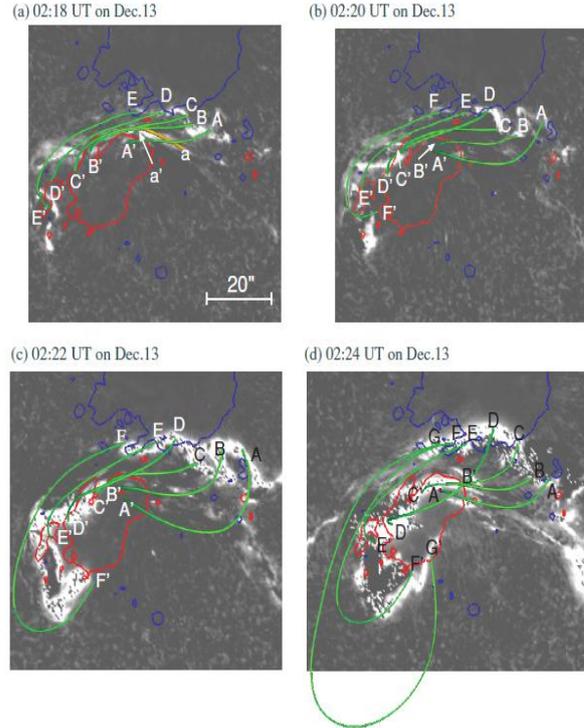


Figure 2. Magnetic field lines (green) plotted on Ca II images (gray scale) for four different times. Field lines are traced from selected points (A to F) on the flare ribbon in the negative pole. The conjugate points in the positive pole are marked by A' to F', respectively. Blue and red lines indicate isocontours for $B_z = -790$ G and 790 G, respectively. Field lines and contours are derived from the magnetogram observed at 20:30 UT on 2006 December 12.

图 5. 11：四个时间的磁力线

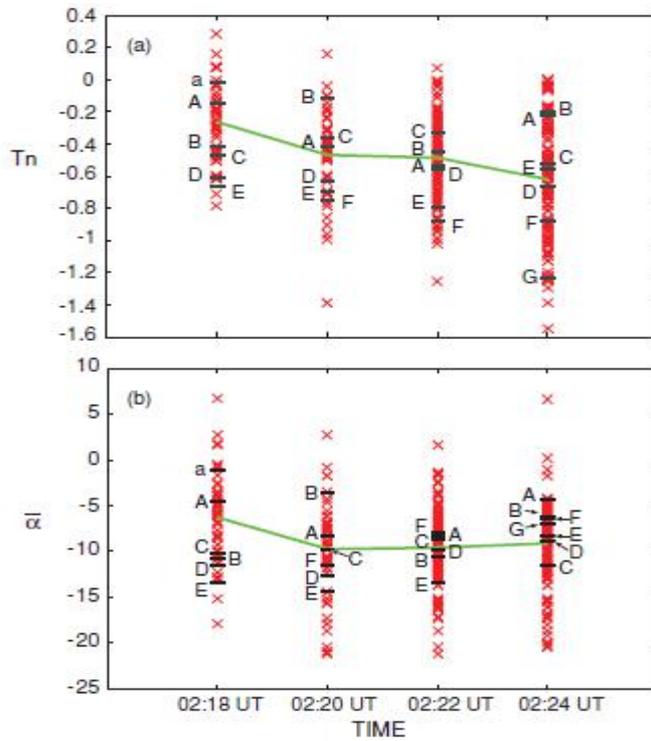


Figure 4. Red crosses represent (a) the twist T_n and (b) the shear parameter $\bar{\alpha}$ of field lines traced from the ribbons shown in Figure 2. A-G in each time correspond to the selected field lines plotted in Figure 2. The solid green lines connect the average values in each time.

图 5. 12：缠绕(a)与剪切参数(b)

5.2.4. 局部缠绕与电流螺度分布

苏等 (2009, APJL 697:L103 - L107) 分析了 NOAA 10930 活动区的局部缠绕 α_z 与电流螺度 h_c 分布, 指出: 1) 在本影区, 正负螺度混合成网状形状, 而在半影区则为线性状; 2) 对主稳定黑子 (MSS), 本影存在正螺度; 对小旋转黑子 (MRS), 本影存在负螺度; 3) 在半影暗条 α_z 和 h_c 的精细分布显示, 相反的螺度可能共存, 且量几乎相等。

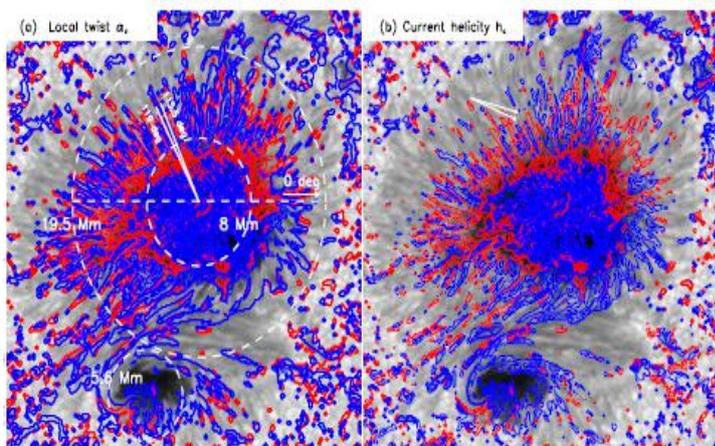


Figure 1. Maps of α_z (a) and h_c (b) for NOAA 10930 at 11:10 UT on 2006 December 11. Red (blue) represents positive (negative) value. The contours of α_z are $\pm 1, 5, 10 \times 10^{-8} \text{ m}^{-1}$ and those of h_c $\pm 0.01, 0.05, 0.1 \text{ G}^2 \text{ m}^{-1}$. The background is continuum intensity image at 630 nm. The field-of-view (FOV) is $76'' \times 76''$ with north up and west to the right. The dashed circles on the two sunspots with the radii of 19.5 Mm and 5.6 Mm limit the regions chosen for our study, and that with a radius of 8 Mm marks partial boundary between the red and blue patches. The two solid lines mark one place of the red and blue thread well paralleling in the penumbra. The two light arrows highlight this place again in the h_c map.

图 5. 13: 局部缠绕 α_z 与电流螺度 h_c 图

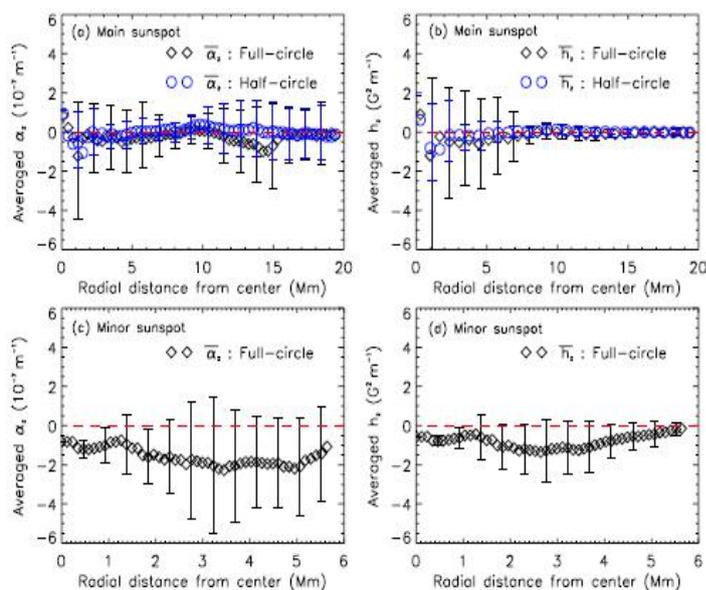


Figure 2. Radial distributions of α_z (a) and h_c (b) from the MSS center. The data are averaged on a series of top half-circles (blue) and full circles (black) in Figure 1. The same are for (c) and (d) from the MRS center but without those half-circle data.

图 5. 14: 主黑子与小黑子的局部缠绕 α_z 与电流螺度 h_c 径向分布图

5.2.5. 日冕磁螺度演化

Park 等 (2010, APJ, 720, 1102 - 1107) 使用 Hinode 及 SOHO 数据利用非线性无力场外推方法研究了 NOAA 10930 在 12 月 8-14 日日冕相对磁螺度的演化性质, 并比较了螺度注入, 发现日冕螺度与螺度积累正相关, 耀斑前不仅有大的负螺度增加, 还有通过磁翻转线附近光球面正螺度的注入。

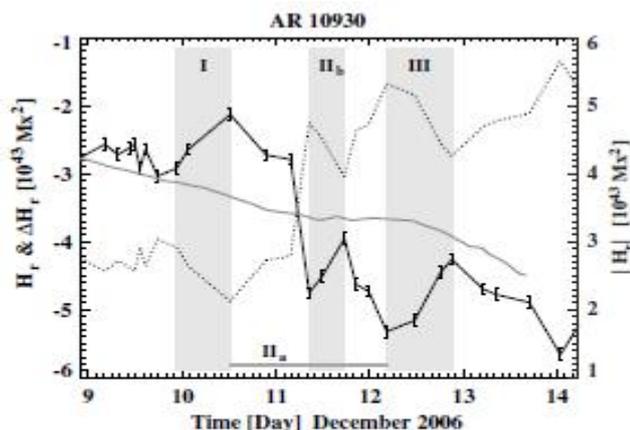


Figure 1. Time variations of the coronal relative magnetic helicity H_r (black solid line with error bars) and the helicity accumulation ΔH_r (gray solid line). The absolute value of H_r decreases for more than 9 hr in the periods marked as I, II_a, and III, while it shows a significant increase of $3.2 \times 10^{43} \text{ Mx}^2$ during the period of II_a. In general, the time profile of H_r shows a good correlation with that of ΔH_r during the entire measurement period.

图 5. 15: 相对螺度及螺度积累演化

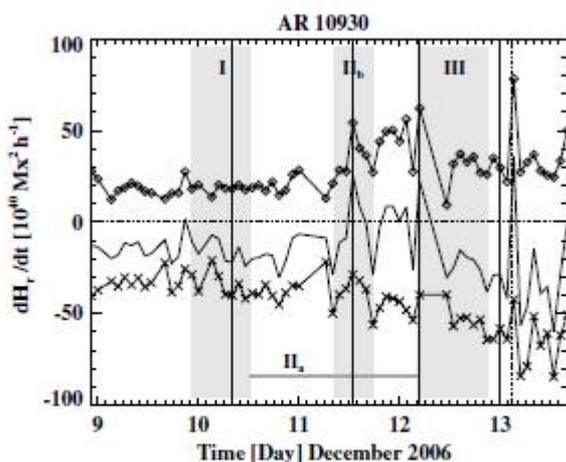


Figure 3. Injection rates of positive helicity (diamonds), negative helicity (crosses), and total helicity (solid line) during the time span of December 8, 20:51 UT to December 13, 16:03 UT. The characteristic periods of I, II_a, II_b, and III are marked in the same way as in Figure 1, and the peak time of the X3.4 flare is shown by the vertical dotted line. The vertical solid lines indicate the times of the investigation of the helicity flux density maps in Figure 3.

图 5. 16: 螺度注入率、负螺度及总螺度演化

5.2.6. 黑子运动与流动场

Wang 等 (2010, Proceedings IAU Symposium , No. 273) 使用 Hinode/SOT 数据, 分析了与 NOAA 10930 耀斑相关的黑子运动与流动场, 发现耀斑前的剪切运动变成非剪切运动, 剪切流平均速度减少与耀斑相关。

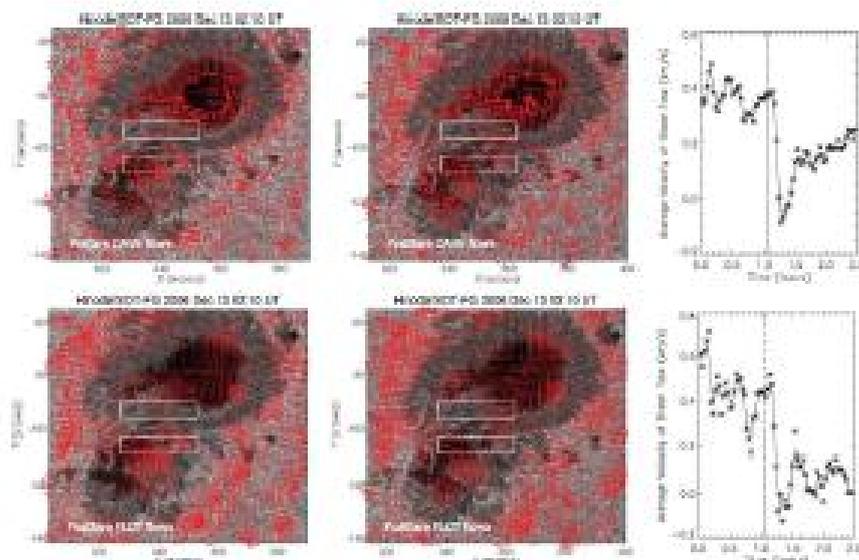


Figure 3. Flow fields for the pre-flare (first column) and post-flare (second column) states derived using the DAVE (upper panels) and FLCT (lower panels) methods. The third column shows the time profile of shear flows calculated as the difference of flows within the two boxed regions, and the start time is 1:10:40 UT 2006 December 13.

图 5. 17: 耀斑前 (左) 后 (中) 的流动场及剪切场 (右)

5.2.7. 黑子旋转速度场

Min & Chae(2009, Solar Physics, 258, 203)利用 Hinode 卫星上 SOT 的 G 段、XRT 和 EIS 数据, 研究了 NOAA10930 活动区黑子的旋转行为, 发现: 1)正极性的小黑子在 5 天内绕中心反时针 540 度; 2) 随着黑子增长, 角速度在 12 月 13 日增加到 8 度/小时, 一天后, 随着黑子的衰退, 迅速减弱到 3 度/小时; 3) 连接两黑子的冕环变成 S 形状; 4) 来自旋转黑子周围的辐射变成蓝移, 表示冕环膨胀。

Figure 4 Velocity field of the small sunspot on 11 December 2006. The field of view is 40'' by 29''. The radius of the circle in the lower-left corner corresponds to a speed of 0.22 km s^{-1} , and the color of an arrow corresponds to its direction.

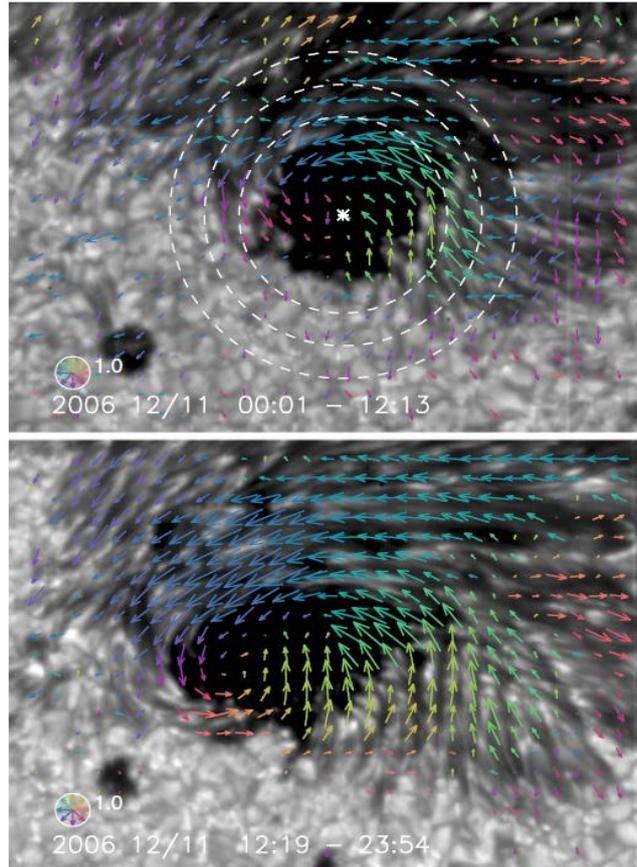


图 5. 18: 2006 年 12 月 11 日小黑子的速度场

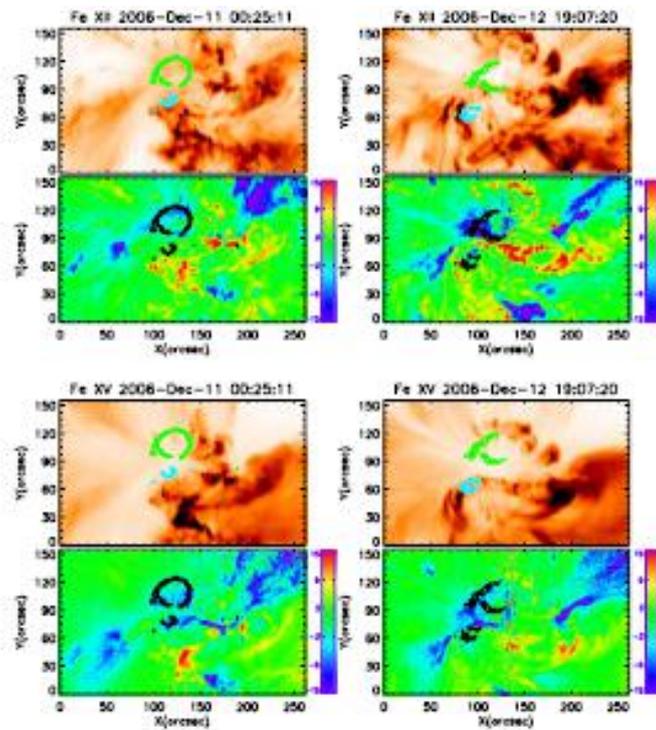


Figure 18 Intensity and Doppler-velocity maps of AR 10930 in Fe XII and Fe XV (velocities are in km s^{-1}).

图 5. 19: NOAA10930 活动区的强度与多普勒速度

5.2.8. 快速黑子旋转与耀斑触发

张军等(2007, ApJ, 662, L35)利用 SOHO/MDI、TRACE 数据,分析了 NOAA 10930 活动区的磁场及黑子演化,发现活动区显著的变化是磁剪切的发展、短暂区的出现极小黑子的快速旋转,在活动区磁中性线附近,快速旋转黑子与短暂区的相互作用触发连续变亮及大耀斑,只有当黑子旋转 200 度以上时才会发生耀斑。

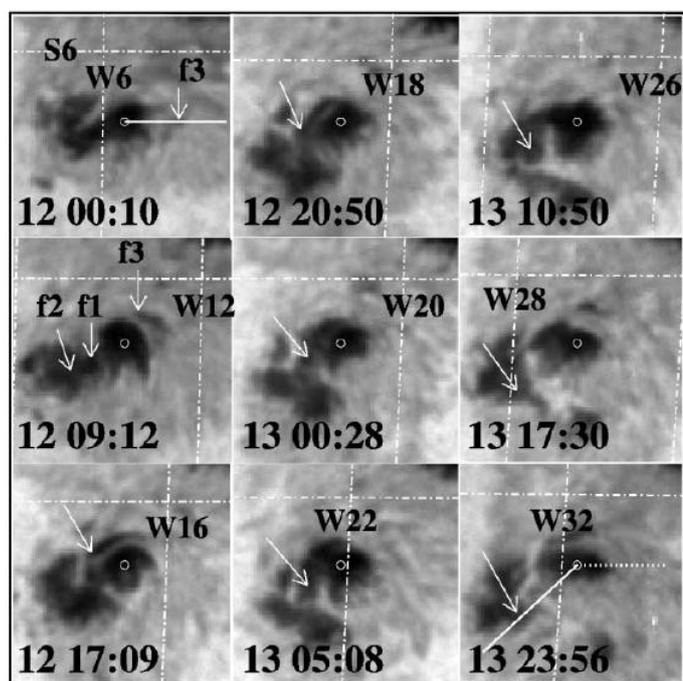


FIG. 5.—Time sequence of *TRACE* continuum images showing the rotation of a dark penumbral feature (f_3) around the center (*circles*) of P1 mentioned in Fig. 1. f_1 and f_2 are other two rotating dark features which appear prior to the emergence of f_3 . The three arrows in the continuum image at December 12, 09:12 UT point to the three features (f_1 , f_2 , and f_3), otherwise the arrows points to f_3 . The convergence of f_1 , f_2 , and other unresolved features forms P2 (see Fig. 1). The two solid lines in the first and last images connect f_3 with the center of gravity of P1, and the dotted line in the last image is a duplicate of the solid line in the first image. The field of view is about $40'' \times 40''$.

图 5. 20: TRACE 图显示半影的旋转

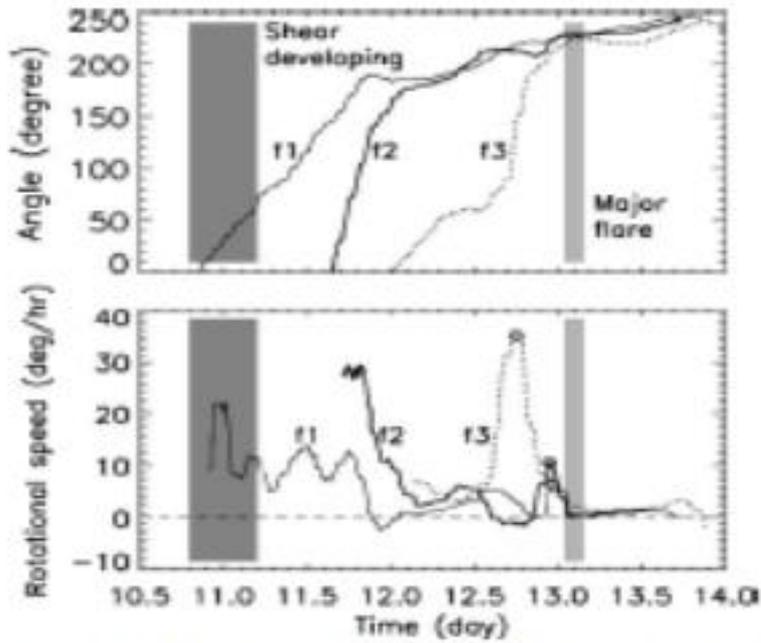


FIG. 6.—Plots showing rotational angle (top) of the three penumbral features (f1, f2, and f3 shown in Fig. 5) and rotational speed (bottom) of the corresponding features vs. time. Dark gray area represents the shear developing period and the light gray area the flaring activity period. The minus rotational speed of these features corresponds to the stage when the features move away from the sunspot. Three circles in the bottom panel are described in the text.

图 5. 21: 旋转角与旋转速度的时间演化

Yan 等 (2009, RAA, 9, 596 - 602) 利用 Hinode 多波段数据, 发现 X3.4 耀斑前正极性的黑子不寻常地逆时针旋转, 沿中性线的磁力线高度剪切, 在黑子旋转之后在日冕内逐渐形成剪切环及反 S 性磁环。

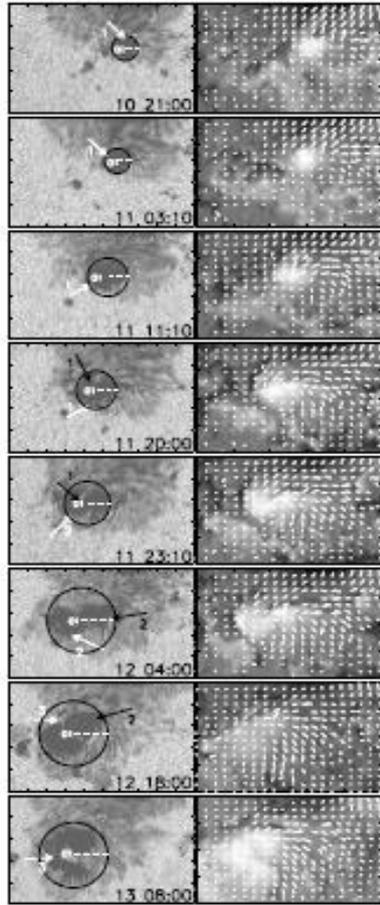


Fig. 3 Rapid rotation of sunspots seen in the sequence of continuous intensity images and vector magnetograms from Spectropolarimeter of SOT. The circle includes the umbra of the rotating sunspot. The arrows in the left panels are specified in detail in the text. The field of view is $75'' \times 45''$.

图 5.22: 快速黑子旋转 (SOT)

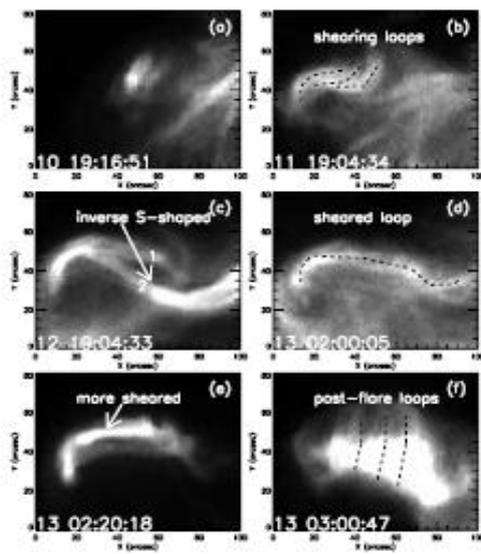


Fig. 5 A series of X-ray images observed with Be-thin filter by XRT of Hinode from 2006 December 10 to December 13. The dashed lines and arrows are described in the text.

图 5.23: 强剪切与反 S 型

5.2.9. 净缠绕电流与净剪切电流演化

Suthar 等 (2014, Solar Phys, 289, 2459 - 2471) 分析了 NOAA 活动区的净缠绕电流 (NTC) 与净剪切电流 (NSC) 的演化, 发现: i) 缠绕电流密度在本影区占主导; ii) 缠绕电流在磁绳浮现的足点占主导; iii) 剪切流与缠绕流密度在本影周围的不同区域; iv) NTC 总大于 NSC; v) 两者在 X3.4 耀斑出现之后都减少了。

Figure 4 The evolution of net current, NTC, and NSC for the whole AR as a function of time.

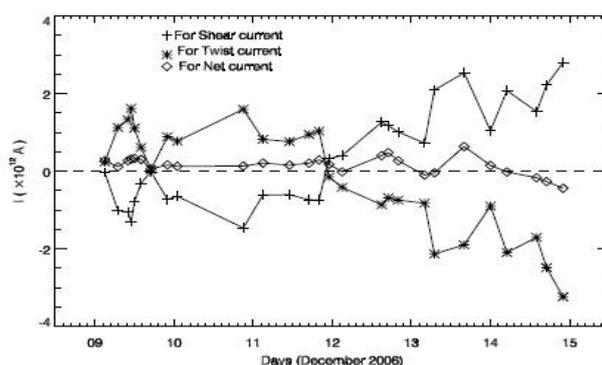


图 5. 24: 净流、NTC 和 NSC 的演化

5.2.10. 半影演化与剪切流

Tan (2009, APJ, 690, 1820 - 1828) 分析了 NOAA10930 耀斑的半影流动及剪切流, 发现: 1) 半影明显衰退; 2) 爆发前有一半半影流动减弱; 3) 耀斑前剪切流开始减弱。

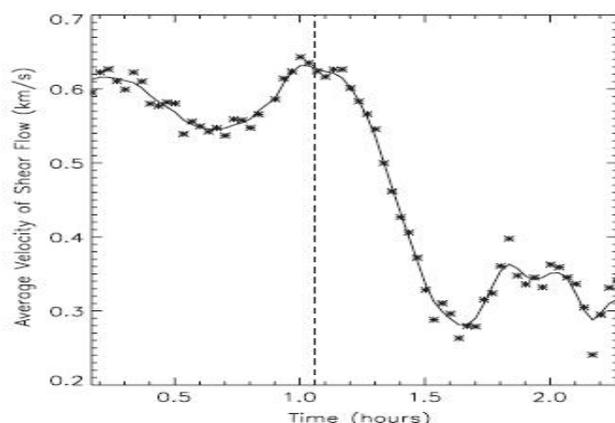


Figure 7. Evolution of shear flows covering the flaring period. The asterisks represent the average velocity of shear flows in the box area A6 in Figure 6. The start time of plot is 1:10:40 UT 2006 December 13. The vertical dashed line indicates the flare time.

图 5. 25: 剪切流演化

5.2.11.沿磁中性线 Evershed 流的快速增强

Deng 等 (2011, APJL, 733, L14) 运用局部相关跟踪技术, 探测到 NOAA 活动区沿磁中性线的 Evershed 流 (水平速度从 330 增加到 403m/s) 的快速增强。

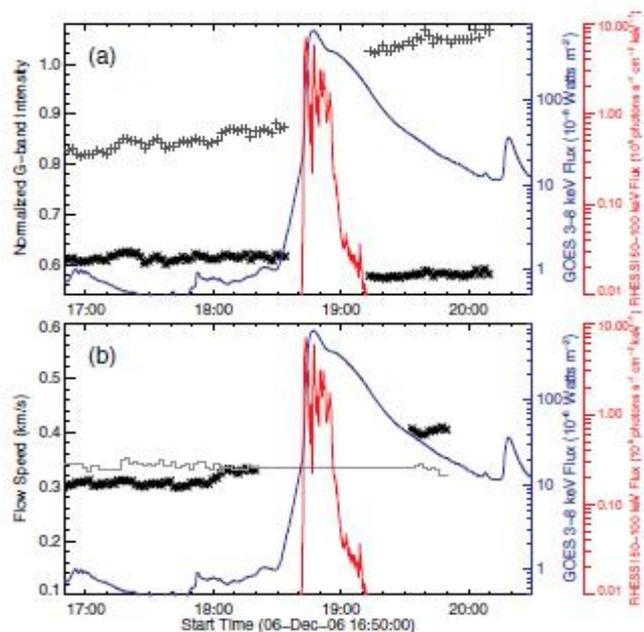


Figure 5. (a) Time profiles of the normalized *G*-band intensity averaged over the ROI (black data points) and outer decayed penumbral regions (gray plus signs). (b) Time profile of the horizontal flow speed averaged in the ROI (black data points). The gray curve as a reference shows the temporal evolution of the flow speed averaged in a stable region outlined by the white box in Figure 3. We exclude the data points during the flare to avoid flare transient effects. Ten data points of flow speed at two ends of each time interval are excluded due to the temporal average algorithm.

图 5.26: G 段强度时间轮廓 (a) 及水平速度时间轮廓

5.2.12. 日冕暗化与 CME

Harra et al. (2007, PASJ, 59, S801) 利用 Hinode EUV 成像 (EIS) 及 SOHO/EIT 195A 数据分析了 NOAA10930 活动区日冕暗化与 CME 的关系, 暗化区域清楚地显示延长的环, 其足点是最强外流的源, 此外, 爆发前在活动区外的暗环处存在一个较弱的外流。

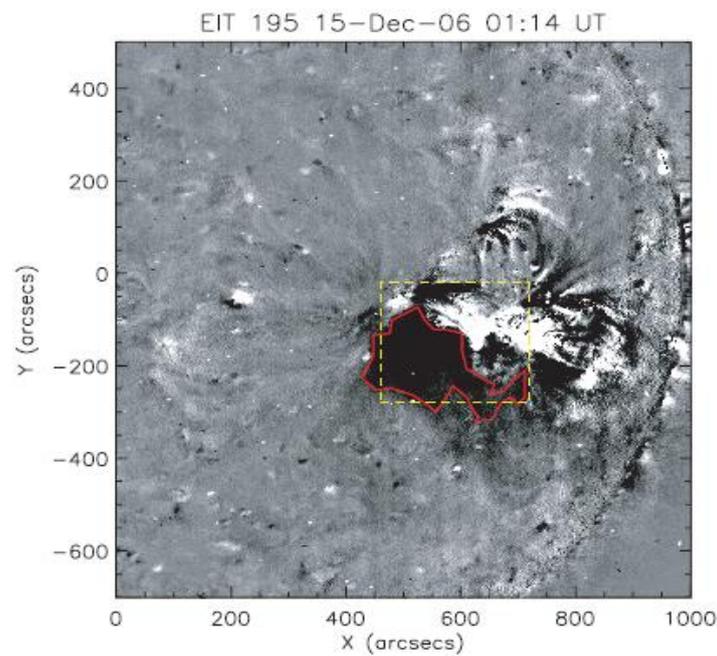


Fig. 2. EIT base difference image with the preflare image at December 14, 21:12 UT subtracted from the image on December 15, 01:14 UT. The EIS field of view is shown by a yellow dashed line. The red contour is the dimming region.

图 5. 27: EIT 较差图显示的暗化区

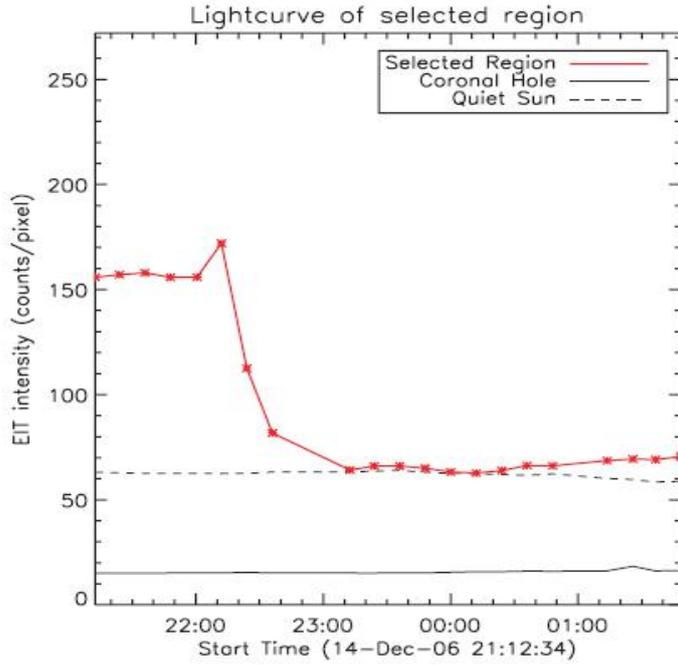


Fig. 3. Light curve of the dimming region marked by the red contour seen in figure 2 from EIT data. There is a sudden decrease of intensity which drops to close to the quiet Sun intensity level (marked with a dashed line). The solid line shows the coronal hole intensity level.

图 5. 28: 暗化区的光变曲线, 显示突然减小

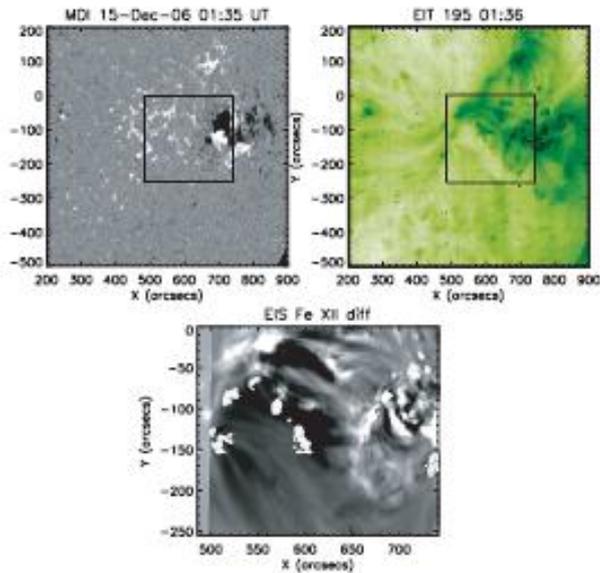


Fig. 7. On the left the magnetogram from MDI is shown with a box illustrating the EIS field of view. On the right the EIT image is shown for context again with a box showing the EIS field of view. The strongest velocities are seen in weak positive polarities in the strong dimming region. The EIS Fe XII intensity difference image with the Doppler velocity contours (blue-shift only) overlaid in white is shown at the bottom. The contour levels range from -10 – 50 km s^{-1} .

图 5. 29: MDI(左)、EIT (右) 与 EIS (下) 观测

5.2.13. Hinode/XRT 观测到的两个 X 级耀斑剪切磁场的演化

Su et al. (2007, PASJ, 59, S785) 利用 Hinode 的 XRT 和 SOT 数据, 通过多波段观测, 分析了 NOAA10930 活动区两个 X 级耀斑(2006 年 12 月 13 和 14 日) 剪切磁场的演化, 指出剪切磁场的逐步形成是由浮现黑子的旋转和东西向运动引起。在耀斑之前, XRT 显示在核的中心场区域存在高度剪切的 X 射线环, 与 TRACE EUV 暗条对应。一部分剪切核场爆发了, 另一部分持续到耀斑后, 这可解释在耀斑之后 TRACE 扔能观测到暗条。大约 2-3 小时后, XRT 再次看到核场, 且内部高度剪切, 而外部低度剪切。耀斑后比耀斑前核场较少剪切, 说明耀斑期间能量释放了。

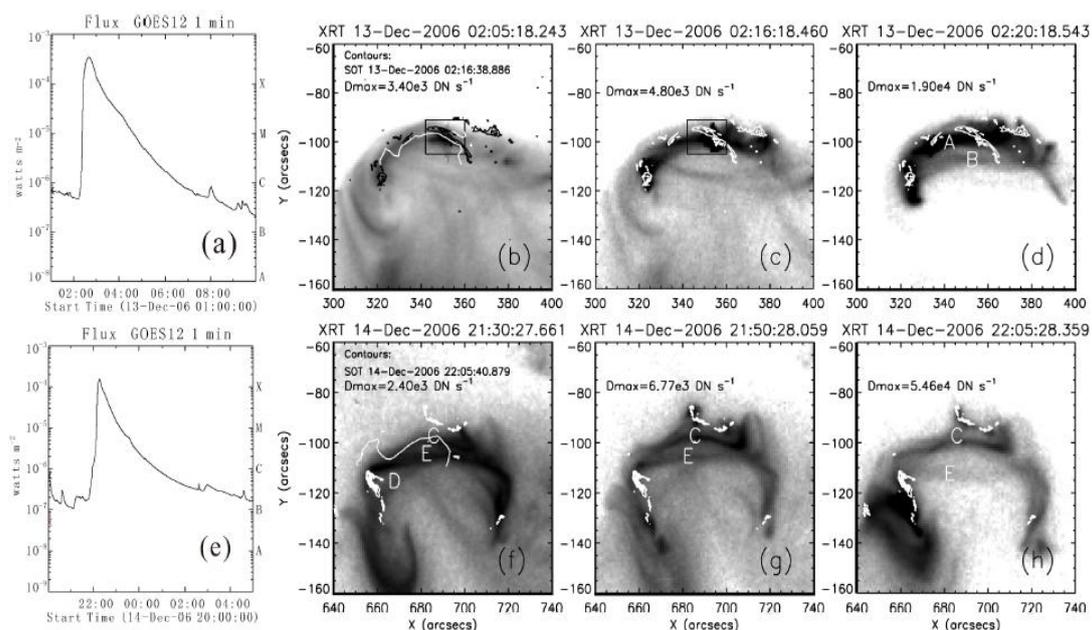


Fig. 3. XRT observations of the sheared magnetic field evolution during two X-class flares. (a) and (e): GOES X-ray time profiles for the 2006 December 13 and December 14 flares. (b) shows an XRT image prior to the December 13 flare, and two XRT images during this flare are presented in (c) and (d). The long-lasting brightening prior to the flare is enclosed by the black box in (b) and (c). The contours in (b)-(d) refer to the brightenings at 02:16 UT observed by SOT in Ca II H. (f)-(h) The XRT images at the early phase of the December 14 flare. The white contours overlaid on these images represent the brightenings at 22:05 UT on December 14 observed by SOT in Ca II H. The white lines in (b) and (f) refer to the SOHO/MDI magnetic inversion line. The maximum intensity (D_{max}) of the XRT image is shown in the upper-left corner of each panel. A-E are the loops discussed in the text.

图 5. 30: 剪切磁场的演化

5.2.14. Moreton 波

Balasubramaniam et al. (2010, ApJ, 723, 587) 讨论了 2006 年 12 月 6 日耀斑的 Moreton 波起源：是耀斑压脉冲还是 CME，动力分析支持 CME 驱动。

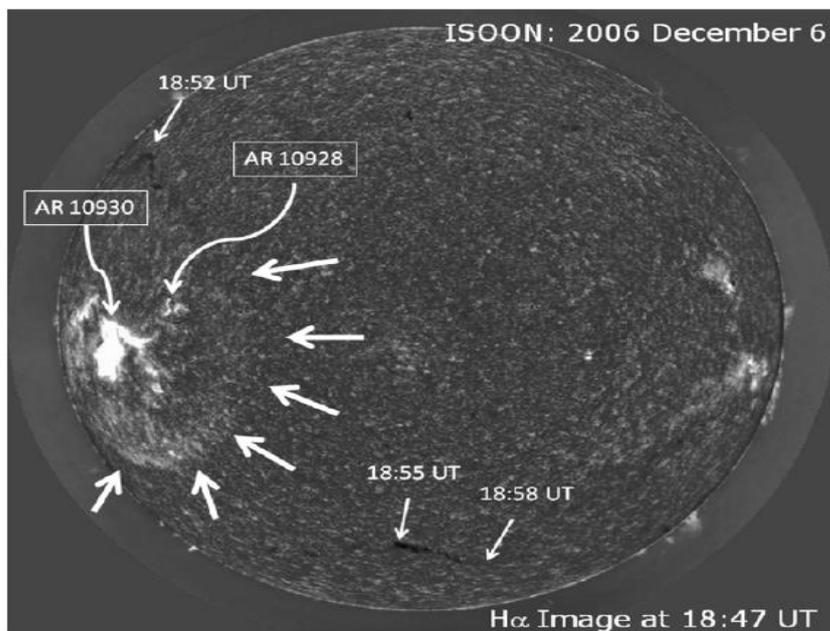


Figure 1. Overview of the solar eruption and Moreton wave of 2006 December 6. The $H\alpha$ image has been scaled to emphasize the wave. The large arrows indicate the position of the wave at 18:47 UT. Smaller arrows indicate the positions of filaments that were disrupted by the wave at the given times as it propagated outward from the AR 10930.

图 5. 31：2006 年 12 月 6 日耀斑爆发与 Moreton 波

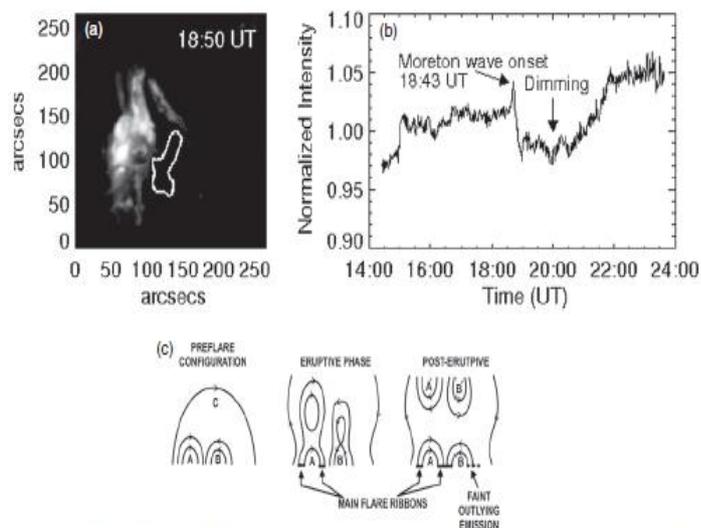


Figure 15. (a) $H\alpha$ centerline image at 18:50 UT with the $H\alpha$ darkening region traced in white. (b) The time intensity plot shows the $H\alpha$ darkening in this region following the eruptive flare. (c) A cartoon taken from Neidig et al. (1997) to illustrate the cause of the darkening—absorption by faint out-lying unresolved post-eruption loops in a weak field region adjacent to the main flare. Note that the magnetic polarities in this figure do not match those for the 2006 December 6 event. They could be easily modified to do so but we show the figure of Neidig et al. (1997) unaltered because of its remarkable resemblance to the 2006 event.

图 5. 32：（a） $H\alpha$ 中心线，（b）强度变化，（c）卡通图

5.2.15. 射电精细结构诊断

Yan 等 (2007, PASJ, 59, S815 - S821) 诊断出 NOAA 活动区存在射电尖型暴、反斜率 III 型暴、U 型暴、V 型暴、脉冲、斑马纹及亚秒尖型斑马结构。

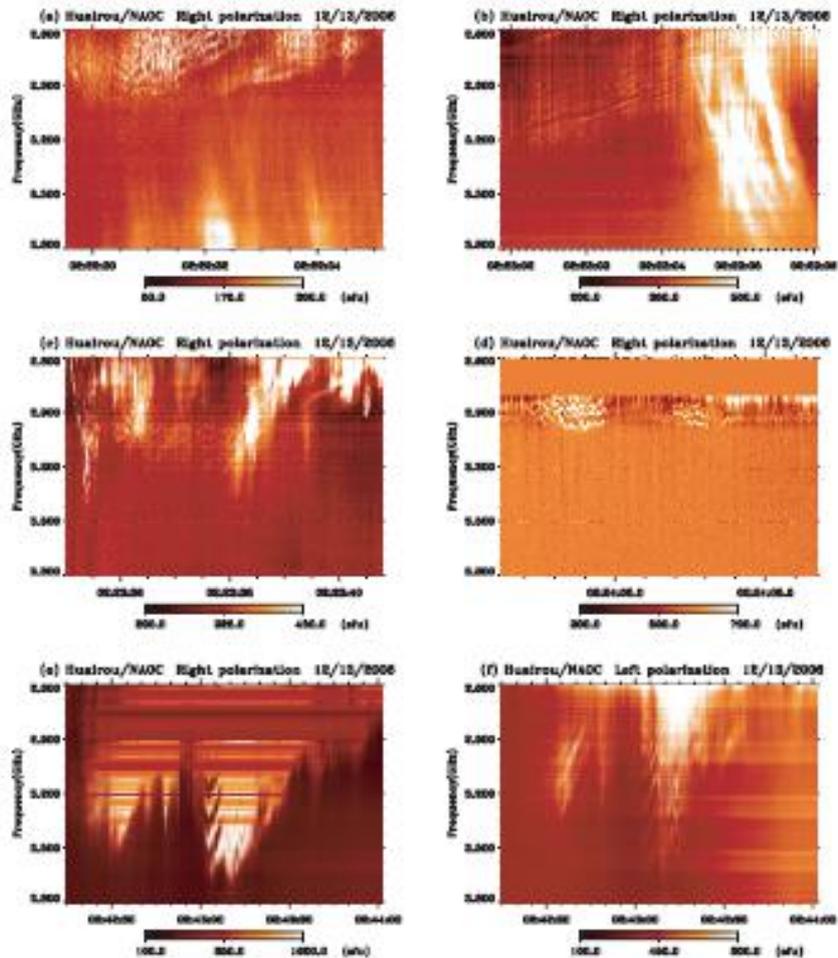


Fig. 2. Dynamic spectra of some fall and strong R19C7 fine structures: (a) first spiky reber pattern structure occurring during 02:22:30-02:22:35 UT; (b) second reber pattern structure mixed with polarization and bright reverse drifting type III bursts during 02:23:02-02:23:06 UT; (c) spikes, reber pattern structure, polarization, and type IV continuum emission during 02:23:35-02:23:40 UT; (d) two sub-second spiky reber patterns with about 0.2 s duration at 02:24:05 UT extending to higher frequencies from the type IV continuum emission; the R19C7 (e) and L19C7 (f) dynamic spectra during 02:42-2:44 UT including a reber pattern structure. The horizontal shadows in (d-e) were due to saturation of the R19C7 component.

图 5.33: 射电诊断

5.2.16.耀斑前后物理参量分布的演化

贺晗等（2014, JGR-Space Physics, 119, 3286）研究了耀斑前后物理参量分布的演化。

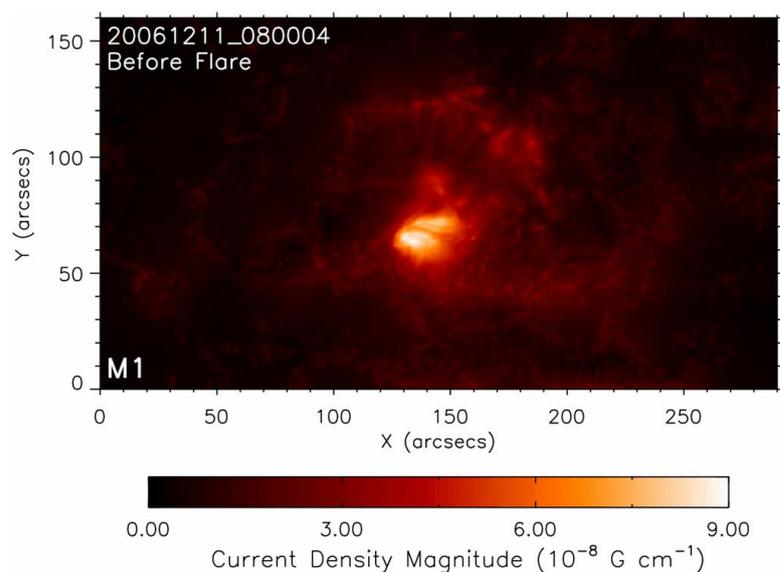


图 5.34：10930 活动区纵向磁场强度（modeling box: 290x160x60）

5.2.17.与运动磁场特征内流相关的毛孔的形成

Li 等（2015, APJ, 807, 160），用 Hinode/SOT 数据，分析了 NOAA10930 活动区与运动磁场特征(MMFs)内流相关的毛孔的形成，1) 在毛孔生长阶段明显存在 MMFs 的内流；2) 观测到的由 MMFs 运输的磁通转移与毛孔磁通强相关；3) 进入毛孔的 MMF 源是在黑子附近产生且沿半影与毛孔的连接线运动；4) 在衰减阶段，毛孔释放磁元的外向流动，毛孔周围的流动不是对称的：内流集中在面向黑子一侧，外流在另一侧。

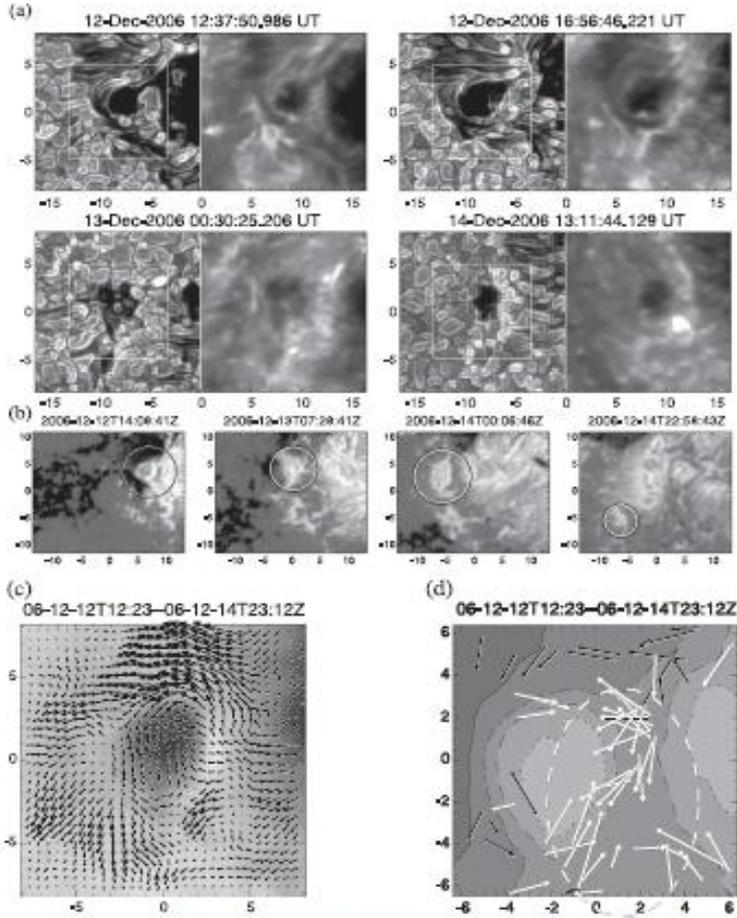


Figure 3. (a) Temporal evolution of a piece of magnetic area that separates from a fragmenting sunspot (No. 2) and forms an individual pore (No. 01, marked with a box). In each panel are displayed simultaneously an edge-enhanced G-band (left) and Ca II H magnetogram (right). (b) Time series of longitudinal magnetograms, with a 12° field of view, showing the evolution of pore-01 (circled). (c) Time-averaged horizontal velocity field measured by Local Correlation Tracking (LCT) method using longitudinal magnetograms. The moving field of view is centered on pore-01. (d) White/black arrows mark the displacements of the positive/negative elements that appear in a 12° × 12° field of view. The background is the contour plot of a time-averaged longitudinal magnetogram, which roughly shows the boundaries of pore-01 (middle) and spot-2 (west). The ellipse accentuates those elements that leave spot-2's penumbra, move across the streak between the sunspot and pore-01, and eventually join the pore.

图 5. 35: 磁场与毛孔的形成

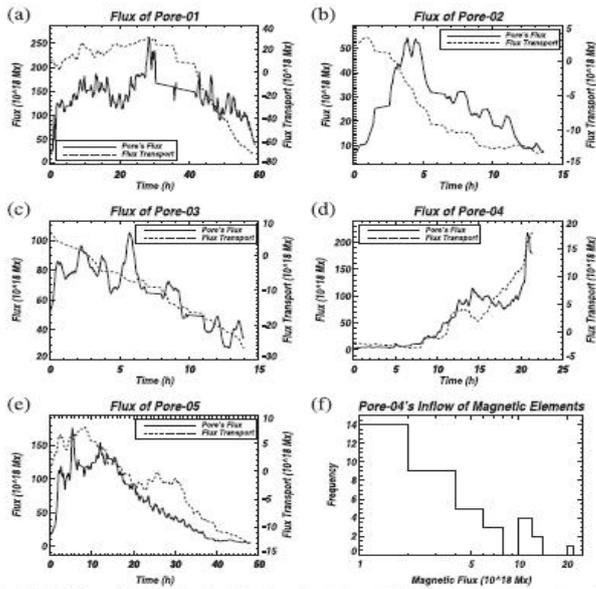


Figure 9. (a)–(e) Solid curves show the temporal evolution of the sample pores' magnetic flux content. Dashed curves show the total flux transport conveyed by magnetic flows. Panels (a)–(e) are measurements from pore Nos. 01–05 respectively. The abscissa in the time starting from the pore's appearance. (f) Frequency distribution of the flux content of the magnetic elements that contribute to pore-04.

图 5. 36: 毛孔磁通与总磁通转移

5.2.18. 高能粒子事件

Malandraki (2009, APJ, 704, 469 - 476) 利用搭载在 Ulysses 的 HI-SCALE and COSPIN/LET 仪器数据, 分析了 NOAA10930 事件期间高能粒子。

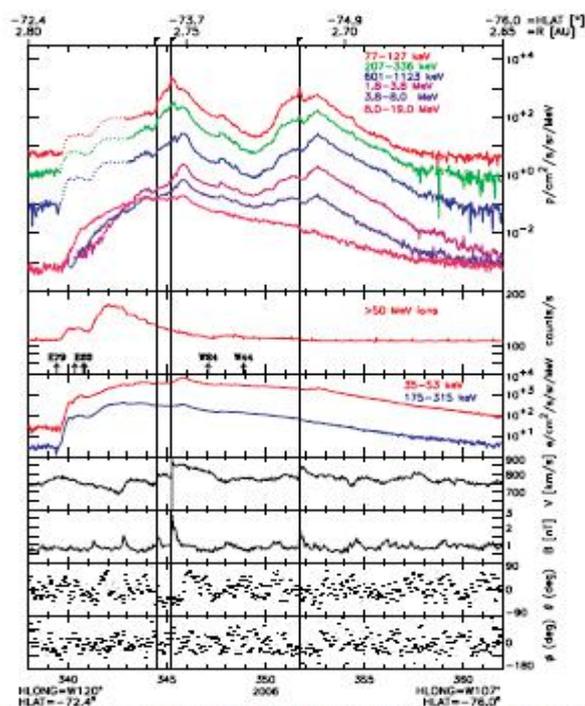


Figure 2. Overview of energetic particle observations as measured by the COSPIN/LET and HI-SCALE instruments onboard Ulysses, solar wind and magnetic field magnitude and direction in 2006 December. Solid vertical lines mark the arrival of interplanetary shock disturbances at Ulysses. Dotted traces in the HI-SCALE/LEMS120 ion time intensity profiles indicate time intervals with possible electron contamination.

图 5. 37: 高能粒子观测 (COSPIN/LET 和 HI-SCALE)

5.2.19. NOAA 10930 和 11158 耀斑的触发过程研究

Bamba 等 (2013, APJ, 778, 48) 使用 Hinode/SOT 数据, 分析了耀斑前磁场结构和钙 II H 发射线的时间-空间相关性, 发现磁剪切角都超过了 70 度, 在耀斑前相就发生了磁场扰动: 一类是反极性, 另一类是反剪切, 非常小的磁场扰动也可能触发大的耀斑。

表 5. 2: NOAA 10930 和 11158 耀斑

Event No.	Date	Start Time ^a (UT)	GOES X-Ray Class	Active Region (AR NOAA)	Location ^b
1	2006 Dec 13	02:14	X3.4	10930	S07W22
2	2006 Dec 14	22:07	X1.5	10930	S06W46
3	2011 Feb 13	17:28	M6.6	11158	S20E05
4	2011 Feb 15	01:44	X2.2	11158	S20W10

Notes.

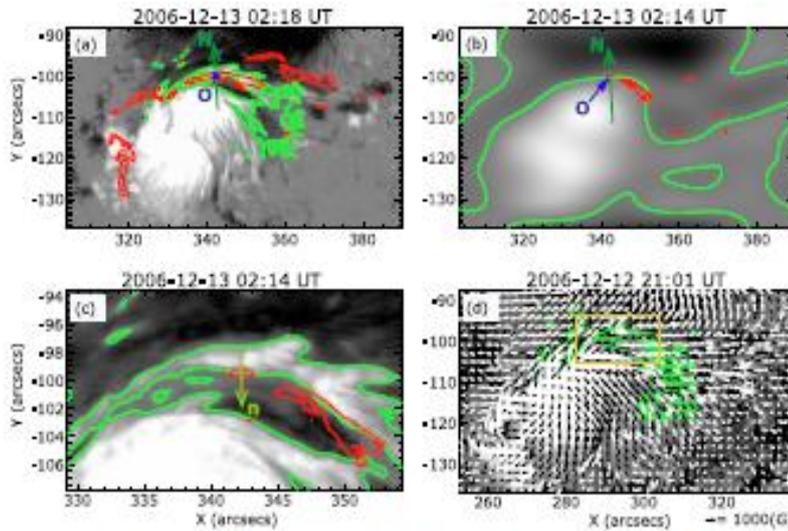


Figure 2. Images of active region NOAA 10930, and vectors N and n on the flare-trigger region in Event 1. The grayscale part of the image corresponds to positive/negative polarity of the L_265 magnetic field (Stokes V/I), and green lines indicate the PIL. The red contours show the Ca II H emission. North is up and the east is to the left. (a) The Stokes- V/I image at 02:18 UT, when the sheared flare ribbon first appeared. (b) The smoothed Stokes- V/I image and the normal vector N at the point O . (c) The enlarged image of (unsmoothed) Stokes V/I and the normal vector n at 02:14 UT. (d) The vector magnetic field obtained by SP at 20:30 UT December 12. The shear angle is calculated as the angle averaged over the yellow square. The grayscale intensity is saturated at 0.1 (Stokes V/I) in (a)-(c) and at $\pm 1000G$ in (d).

(A color version of this figure is available in the online journal.)

图 5. 38: NOAA 10930 活动区事件 I Stokes-V/I 分布

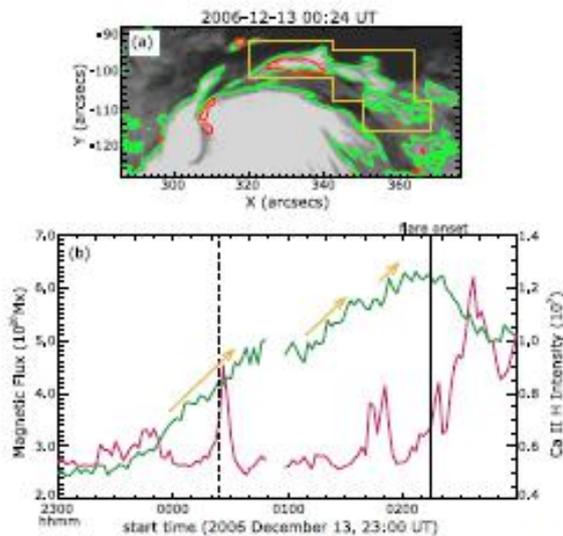


Figure 3a. (a) Stokes- V/I image in the flare-trigger region of Event 1. Gray scale is saturated at $\pm 5000G$. The yellow rectangle indicates the region where magnetic flux and Ca II H intensity are integrated. The green lines are the PILs and the red contours indicate Ca II H emission. (b) Time evolution of positive magnetic flux and Ca II H intensity integrated in the yellow rectangle in panel (a). The vertical solid line marks the onset time of the flare, 02:14 UT 2006 December 13, and the dashed line corresponds to the time of panel (a). The green and pink curves plot positive magnetic flux and Ca II H intensity, respectively.

(A color version of this figure is available in the online journal.)

图 5. 39: (a)NOAA 10930 活动区事件 I Stokes-V/I 分布, (b)正磁通与钙 II 线强度演化

5.2.20. 旋转与缠辩螺度演化

Ravindra 等 (2011, APJ, 743, 33) 使用 Hinode/SOT/SP、SOT/NFI 数据, 分析了 NOAA 活动区的旋转 (spinning) 与缠辩 (braiding) 螺度演化, N 级黑子为后随, S 级黑子为前导, N 级黑子逆时针旋转, S 级黑子 5 天内旋转不断 20 度, 但 5 次改变方向, 并注射正、负两者旋转螺度到日冕, 总注射螺度为负螺度, 整个区域的旋转与缠辩螺度在 5 天内从负到正 5 次改变符号, 且发生在 X3.4 耀斑前。

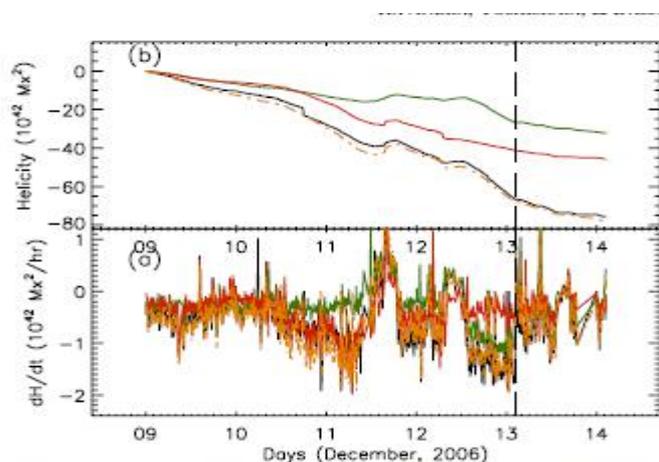


Figure 8. (a) Temporal evolution of the rate of spinning (green), braiding (red), and sum of these two (dash-dotted yellow line) helicity fluxes for all the partitions in the region taken into account. The black curve represents the rate of change of helicity flux estimated independently using Equation (3). (b) Temporal evolution of total accumulated spinning (green), braiding (red), and spin + braiding (dash-dotted) helicities of all the regions taken into account. The black curve represents the total integrated helicity estimated independently. The dark vertical line represents the onset time of the X3.4-class flare. In the x-axis, major and minor tick marks represent the days and time of 2006 December.

图 5. 40: 旋转、缠辩螺度及其和的时间演化

5.2.21. 预报 X 射线强度

Tiwari (2010, APJ, 721, 622 - 629) 发现利用空间上平均剪切角 (spatially averaged signed shear angle, SASSA) 可以较好地对 X 射线强度进行预报, 另外, 平均加权剪切角 (mean weighted shear angle, MWSA) 预报效果不理想。

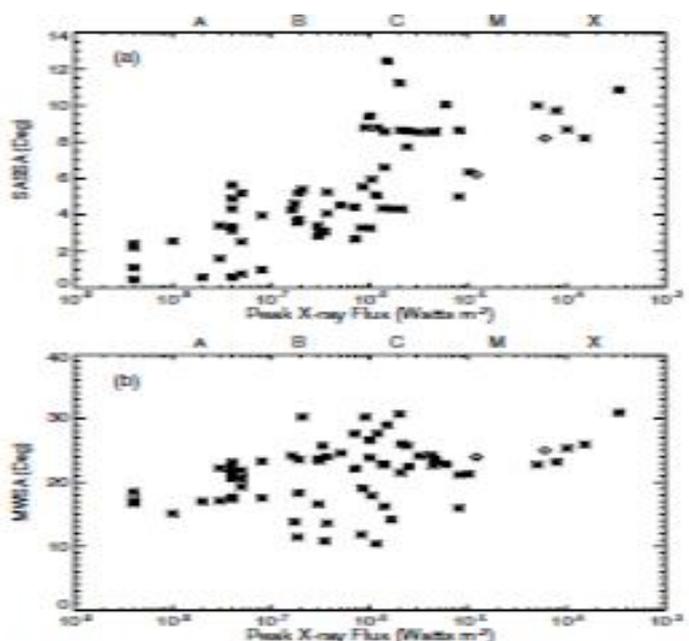


Figure 5. (a) Scatter plot between the SASSA and peak X-ray flux of the GOES 12 satellite. Samples include all the events associated with all four active regions, i.e., NOAA ARs 10930, 10960, 10961, and 10963. The magnitude of the SASSA at the time of the peak X-ray flux has been interpolated from the available sample of the SASSA, as shown in Figures 3 and 4. Also, the approximate values of the SASSA corresponding to M-class flares in two cases have been taken from Table I of Tiwari et al. (2009b) and are shown by diamond symbols. (b) The same as panel (a), except for values of the MWSA instead of the SASSA.

图 5. 41: X 射线强度与 SASSA(a)及 MWSA 的散点关系图

5.2.22. 用数据驱动 MHD 模拟方法研究 NOAA10930 活动区的波印廷通量

范玉良等 (2011, APJ, 737, 39) 利用与时间相关的多维 MHD 模拟方法采用波印廷通量来研究产生耀斑的磁场变化, 随时间变化的边界条件由正投影特征方法得到, 这样, 光球磁图可以自洽的作为数据驱动的底部边界条件。他们把这种模型第一次用到浮现磁通上, 并用作 Hinode/SOT 在 2006 年 12 月 13 日观测到的 NOAA 10930 活动区 (X3.4 耀斑), 他们在四个区域: 整个黑子、正极黑

子、负极黑子及强磁场中性翻转线(SPIL)计算了并分析了总波印廷通量(S_{total}), 径向分量(S_z), 理想径向分量 (S_{proxy})、由于等离子体表面运动引起的波印廷通量 (S_{sur})和由于等离子体浮现引起的波印廷通量(S_{emg})。发现：(1) S_{total} , S_z , 和 S_{proxy} 在整个黑子区域及负极黑子区域行为相似, 而由于黑子旋转及通量浮现的原因在正极区域及 SPIL 比较不稳定；(2) S_{sur} 的时间演化受黑子旋转过程的影响比较大, 特别是在正极黑子附近, S_{emg} 的演化大大地受通量浮现的影响, 特别是在 SPIL 区域。

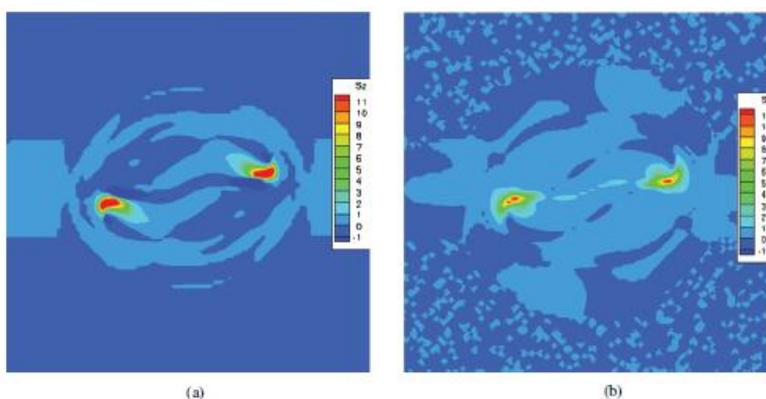


Figure 1. Left: radial Poynting flux contour from the emerging flux rope simulation. Right: radial Poynting flux contour from the data-driven simulation using the bottom boundary data of the emerging flux rope.

图 5. 42: 由浮现通量绳模拟的径向波印廷通量轮廓 (左) 及根据浮现通量绳数据作为底边界条件用数据驱动方法得到的径向波印廷通量轮廓 (右)

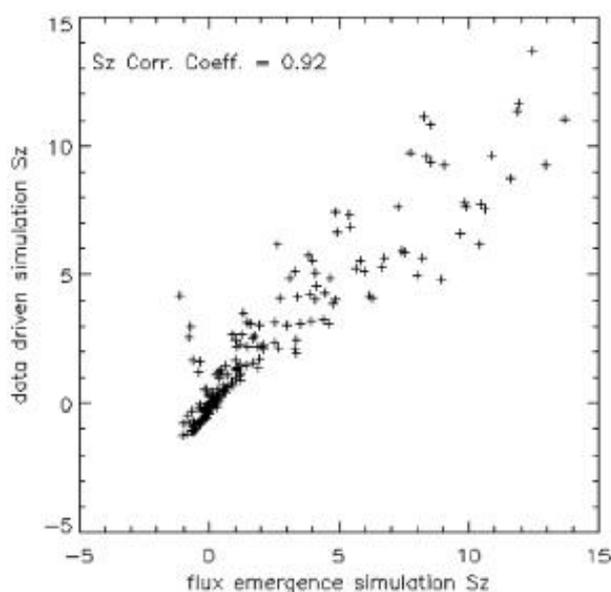


Figure 2. Scatter plot of the distribution of radial Poynting flux S_z from the data-driven simulation vs. the distribution of radial Poynting flux S_z from the emerging flux simulation.

图 5. 43: 用数据驱动及用浮现通量模拟得到的径向波印廷通量对比

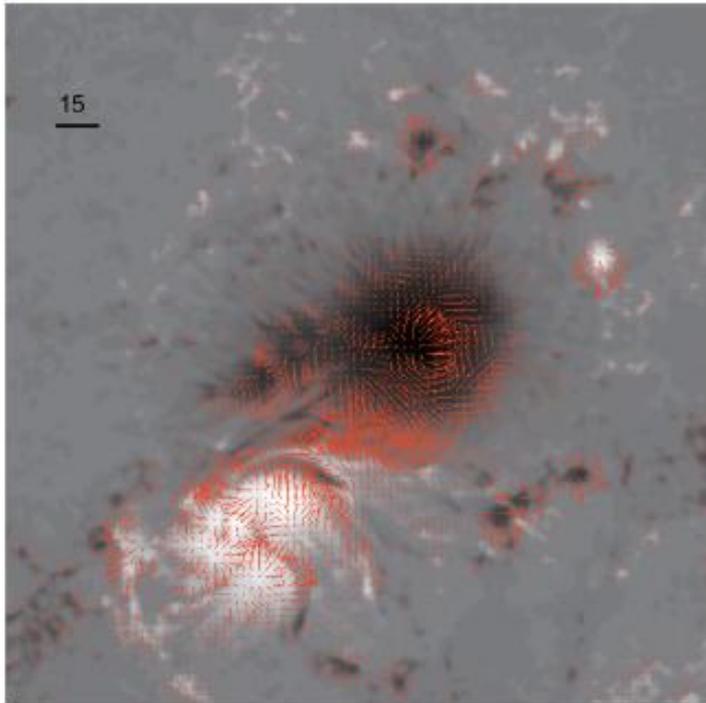


Figure 5. Longitudinal magnetogram for NOAA 10930 at 04:30 UT 2006 December 13, overlapped with the transverse velocity field map in red. The units of velocity are 15 km s^{-1} .

图 5. 44: NOAA 10930 活动区在 2006 年 12 月 13 日 04:30 UT 的纵向磁图及横向速度

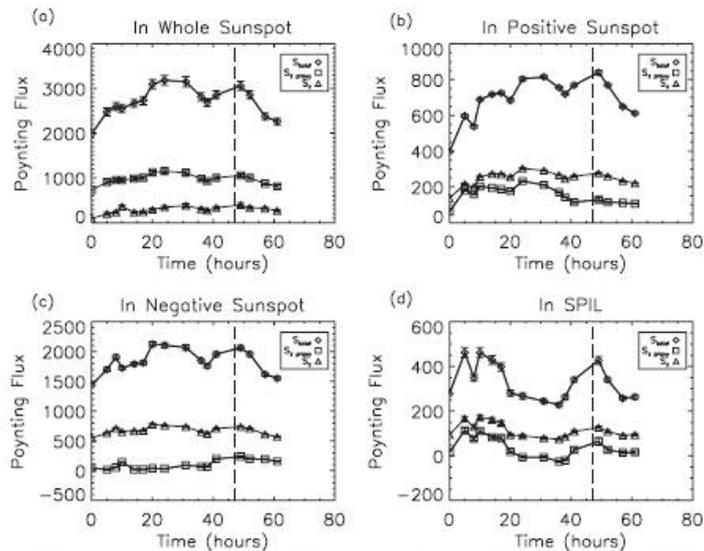


Figure 7. Evolution of the total Poynting flux (S_{total}), the radial Poynting flux (S_z), and a crude proxy for the ideal radial Poynting flux (S_{proxy}) for four areas: the whole sunspot, the positive sunspot, the negative sunspot, and SPIL for NOAA 10930. The beginning magnetogram is at 03:10 UT on 2006 December 11 and the ending magnetogram is at 16:21 UT on 2006 December 13. The vertical dashed line indicates the occurrence of flare X3.4. The Poynting flux is in units of $2.1 \times 10^{26} \text{ erg s}^{-1}$.

图 5. 45: NOAA 10930 活动区从 2006 年 12 月 11 日 03:10 UT 至 2006 年 12 月 13 日 16:21 UT 的纵向磁图及横向速度在整个黑子、正极黑子、负极黑子及 SPIL 四个区域的总波印廷通量 (S_{total})、径向分量(S_z 及理想径向分量 (S_{proxy}))的演化

5.3. 主要科学贡献

● 多波段成像综合成像研究

高精度的 hinode/SP 矢量磁场观测为多波段成像观测（光球、色球、日冕）提供了很好的案例。

➤ 磁场拓扑结构研究

高精度的 hinode/SP 矢量磁场观测为分析磁场的拓扑结构提供了条件。

➤ 活动区磁场外推研究

精确度的 hinode/SP 矢量磁场观测大大促进了非线性无力场磁场外推方法的研究和使用。

➤ 电流研究

在耀斑之前强电流与磁图同时出现，这些电流出现在薄层集合中，这些电流和场线的整体结构与大规模缠绕磁绳拓扑共处。

射线强度对电流强度比对场线缠绕更敏感，即使缠绕较弱，电流也较强，而活动区外，缠绕较强，电流较弱。

拓扑看表示为一个高度剪切的核场核准势包罗的拱场，核场显示一些坑来维持暗条，耀斑后自由能减小。

NLFFF 构造的磁力线足点对应高剪切耀斑带的共轭对；在耀斑早期，随着耀斑带远离磁极翻转线，根植于耀斑带的磁力线缠绕增加；在耀斑开始前的一天内，磁通缠绕且逐渐增加，而在耀斑后的时间内迅速减小。

缠绕电流密度在本影区占主导；缠绕电流在磁绳浮现的足点占主导；剪切流与缠绕流密度在本影周围的不同区域。

● 物理参量研究

➤ 电流螺度研究

日冕螺度与螺度积累正相关，耀斑前不仅有大的负螺度增加，还有通过磁翻转线附近光球面正螺度的注入。

在本影区，正负螺度混合成网状形状，而在半影区则为线性状；对主稳定黑

子，本影存在正螺度；对小旋转黑子，本影存在负螺度；在半影暗条，相反的螺度可能共存，且量几乎相等。

➤ 磁螺度研究

日冕螺度与螺度积累正相关，耀斑前不仅有大的负螺度增加，还有通过磁翻转线附近光球面正螺度的注入。

➤ 磁剪切研究

剪切磁场的逐步形成是由浮现黑子的旋转和东西向运动引起，在耀斑之前在核的中心场区域存在高度剪切的 X 射线环，与 TRACE EUV 暗条对应。大约 2-3 小时后，XRT 再次看到核场，且内部高度剪切，而外部低度剪切。耀斑后比耀斑前核场较少剪切，说明耀斑期间能量释放了。

➤ 数据驱动 MHD 模拟研究波印廷通量

利用与时间相关的多维 MHD 模拟方法研究活动区的波印廷通量，发现：(1) 总波印廷通量(S_{total})、径向分量(S_z)和理想径向分量 (S_{proxy})在整个黑子区域及负极黑子区域行为相似，而在正极区域及磁中性翻转线 (SPIL) 比较不稳定；(2) 由于等离子体表面运动引起的波印廷通量 (S_{sur})的时间演化受黑子旋转过程的影响比较大，特别是在正极黑子附近，由于等离子体浮现引起的波印廷通量 (S_{emg}) 的演化大大地受通量浮现的影响，特别是在 SPIL 区域。

➤ 用数据驱动 MHD 模拟方法研究波印廷矢量

利用与时间相关的多维 MHD 模拟方法研究波印廷矢量在黑子四个不同区域区域 (整个黑子、正极黑子、负极黑子及强磁场中性翻转线)中的演化，发现：(1) 总波印廷通量(S_{total})，径向分量(S_z)，理想径向分量 (S_{proxy})在整个黑子区域及负极黑子区域行为相似，而由于黑子旋转及通量浮现的原因在正极区域及 SPIL 比较不稳定；(2) 由于等离子体表面运动引起的波印廷通量 (S_{sur})的时间演化受黑子旋转过程的影响比较大，特别是在正极黑子附近，由于等离子体浮现引起的波印廷通量(S_{emg}) 的演化大大地受通量浮现的影响，特别是在 SPIL 区域。

● 运动与机制研究

➤ 黑子运动与流动场

耀斑前的剪切运动变成非剪切运动，剪切流平均速度就减少与耀斑相关。

沿磁中性线的 Evershed 流的快速增强。

➤ 黑子旋转速度场

正极性的小黑子在开始绕中心反时针旋转；随着黑子增长，旋转角速度增加，随着黑子的衰退，迅速减弱，连接两黑子的冕环变成 S 形状，来自旋转黑子周围的辐射变成蓝移，表示冕环膨胀。

在活动区磁中性线附近，快速旋转黑子与短暂区的相互作用触发连续变亮及大耀斑，只有当黑子旋转 200 度以上时才会发生耀斑。

耀斑前正极性的黑子不寻常地逆时针旋转，沿中性线的磁力线高度剪切，在黑子旋转之后在日冕内逐渐形成剪切环及反 S 性磁环。

➤ Moreton 波

Moreton 波起源：是耀斑压脉冲还是 CME？动力分析支持 CME 驱动。

➤ 射电精细结构诊断

活动区存在射电 尖型暴、反斜率 III 型暴、U 型暴、V 型暴、脉冲、斑马纹及亚秒尖型斑马结构。

➤ CME 机制研究

暗化区域清楚地显示延长的环，其足点是最强外流的源，爆发前在活动区外的暗环处存在一个较弱的外流。

➤ 与运动磁场特征内流相关的毛孔

在毛孔生长阶段明显存在运动磁场特征的内流；观测到的由运动磁场特征运输的磁通转移与毛孔磁通强相关；进入毛孔的运动磁场特征源是在黑子附近产生且沿半影与毛孔的连接线运动；在衰减阶段，毛孔释放磁元的外向流动，毛孔周围的流动不是对称的：内流集中在面向黑子一侧，外流在另一侧。

➤ 耀斑的触发过程研究

耀斑前磁剪切角都超过了 70 度，在耀斑前相就发生了磁场扰动：一类是反极性，另一类是反剪切，非常小的磁场扰动也可能触发大的耀斑。

- 高能粒子事件

- 该事件期间发生了 4 个高能粒子事件。

- 预报 X 射线强度

- 利用空间上平均剪切角可以较好地 对 X 射线强度进行预报。

5.4. 影像观测资料

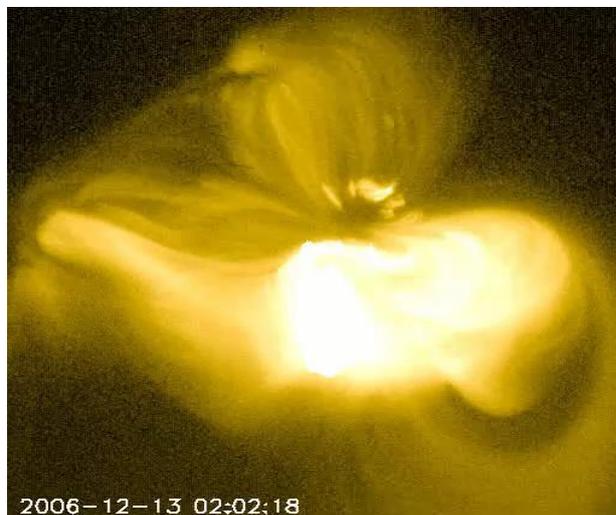


图 5. 46: 2006 年 12 月 13 日 Hinode/XRT 观测到的 X 级耀斑 (X3.4 0214 0240 0257)

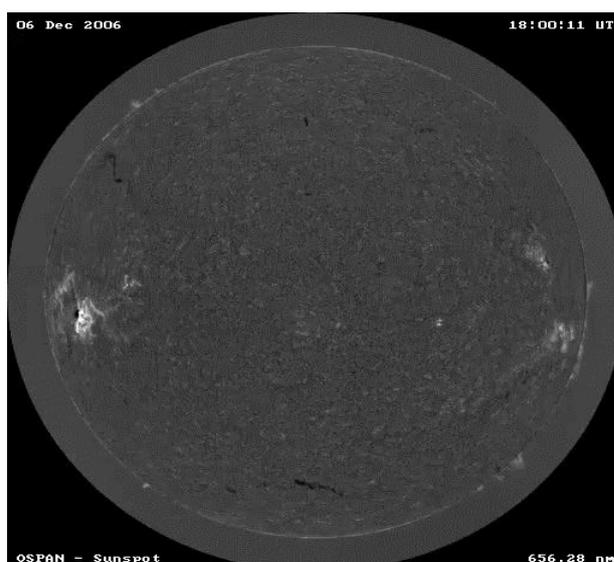


图 5. 47: 2006 年 12 月 6 日色球 H-alpha 观测的 X 级耀斑 (X6.5 1829 1847 1900)

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第六章 NOAA11158 活动区事件

6.1. 事件概述

NOAA 11158 活动区于 2011 年 2 月 12 日出现，2 月 21 日消失，最大时日面面积为 620，磁位型为 $\beta\gamma\delta$ ，产生了 1 个 X2.2 级的 X 级耀斑、6 个 M 级耀斑，7 个 CME 事件，只有 2 月 15 日指向地球全晕 CME。

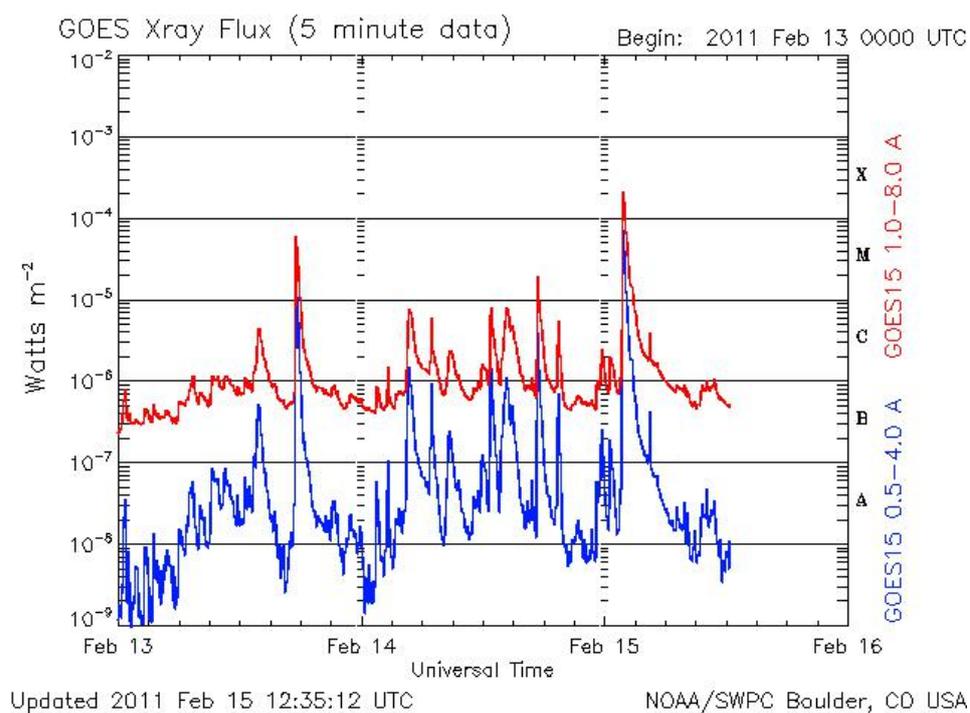


图 6.1: NOAA11158 活动区 GOES 流量图

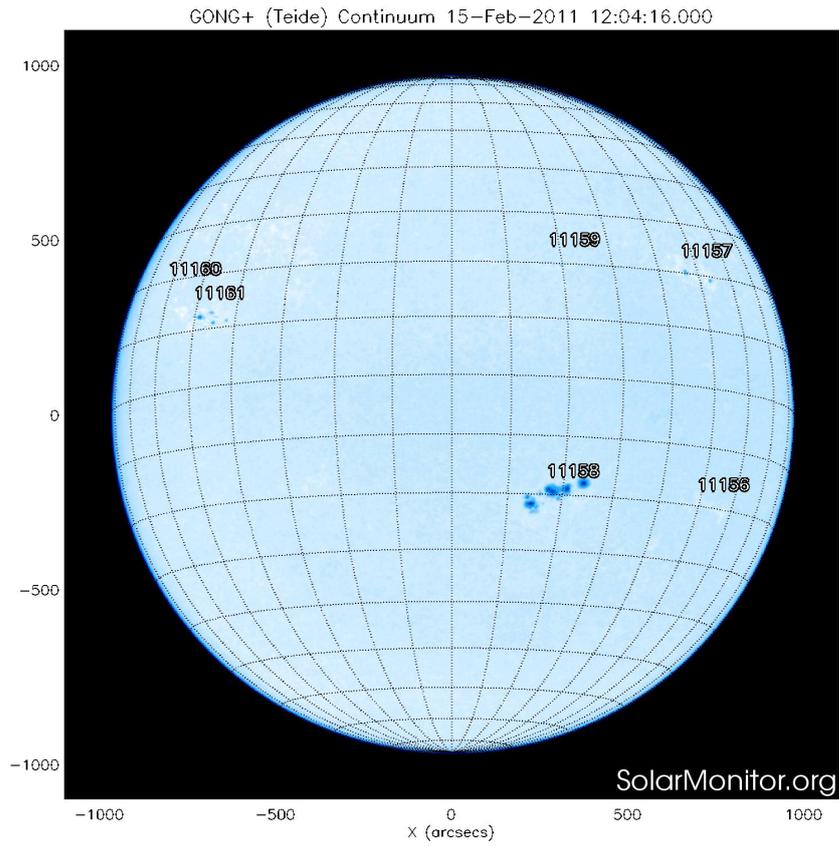


图 6. 2: NOAA11158 活动区黑子图 (GONG)

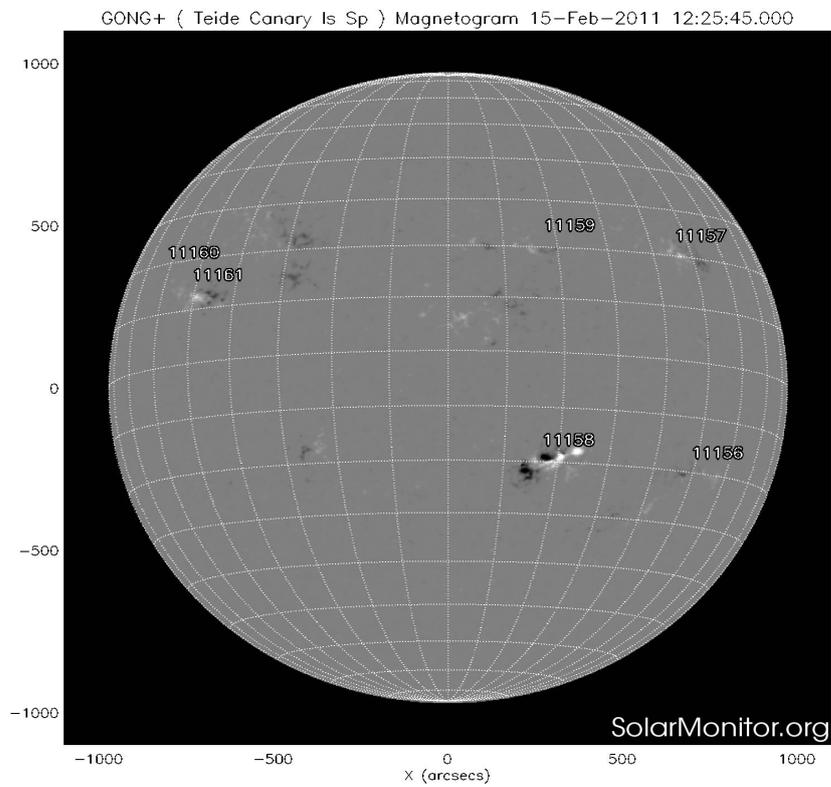


图 6. 3: NOAA11158 活动区磁图 (GONG)

6.1.1. 事件特征

- 事件观测时间：2011 年 2 月 12 日到 2 月 21 日
- 最大面积：620 日面单位；时间：2011 年 2 月 17 日；位置：S21W39
- 磁位型： $\beta\gamma\delta$
- X 级耀斑数量：1
- M 级耀斑数量：6
- 产生的最大耀斑：X2.2；时间：2011 年 2 月 15 日 01:56UT；位置：-
- CME 事件：7 个 CME 事件，其中 2 月 15 日指向地球全晕 CME
- 日地效应：地磁指数：Dst=-32, kp=5(2 月 18 日)

6.1.2. 观测特征

2011 年 2 月 15 日快速通量浮现及强剪切（磁剪切角都超过了 70 度）运动导致一个四极磁场，形成第 24 太阳活动周的第一个 X 级耀斑（X2.2）耀斑及向地全晕 CME，还产生了 II 型及 III 型射电暴。

6.2. 相关事件案例研究

NOAA11158 事件产生了第 24 太阳活动周的第一个 X 级耀斑，有关 AR11158 的文章有上百篇，研究内容大致涵盖：活动区磁场、非势能、拓扑结构、电流、螺度、速度场等的演化、黑子的转动效应、耀斑及 CME 的触发机制探讨等。

6.2.1. 大爆发活动区的磁场及能量演化

Sun 等（2012, APJ, 748, 77）基于 SDO/HMI 数据分析了 NOAA 11158 活动区 5 天中磁场及其能量演化。快速通量浮现及强剪切运动导致一个四极复杂黑子，从而产生了几大的爆发，包括第 24 太阳活动周的第一个 X 级耀斑。非线性无力场外推日冕磁场显示，在暗条通道中处于低位的千高斯剪切场的 S 性暗条

附近早期通量浮现期间，有大量的电流及自由能增加，计算出的磁自由能的最大值（ $\sim 2.6 \times 10^{32}$ erg）达到了在 6Mm 以下储存值的 50%左右，在 X 耀斑的一个小时内以 $\sim 0.3 \times 10^{32}$ erg 速率减少，这很可能低估了实际能量损失。耀斑期间光球场快速变化：在核心区水平场提高了 28%，变得更倾斜、更与极性翻转线平行，这种变化与推测的日冕场“爆炸”一致，并被 AIA 观测的日冕环回缩支持。在耀斑之后，外推场变得更加“紧致”，可能是由于重联的原因在核心区环较短，在最低层，日冕场变得更剪切，随着高度释放的更快，总体活力不足。

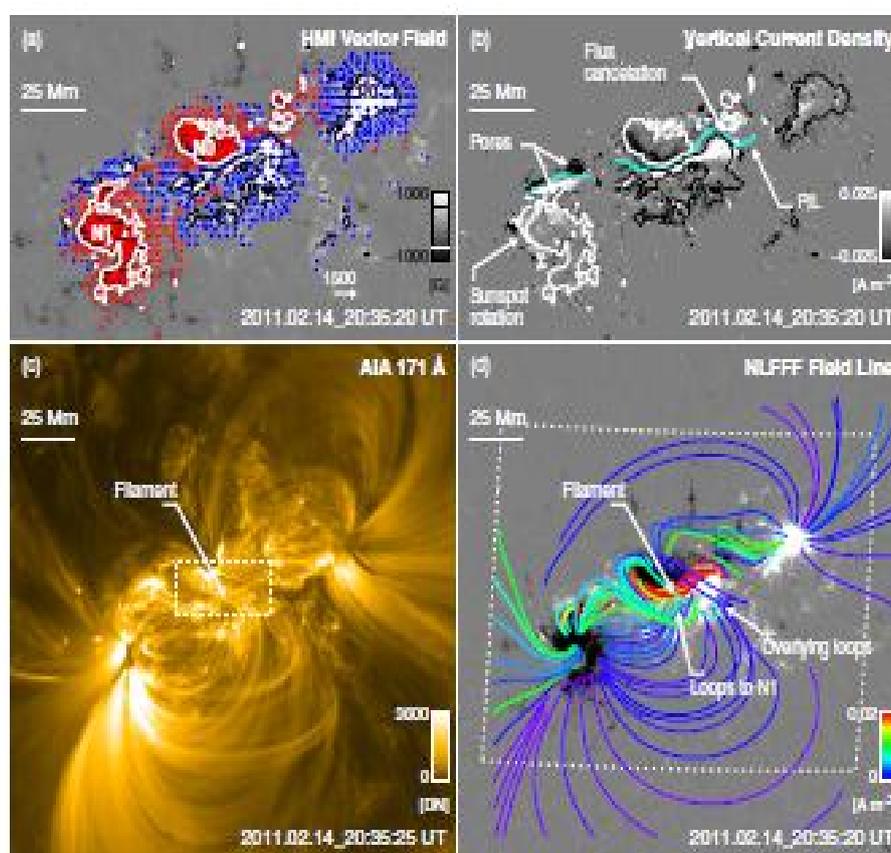


Figure 1. Observations and modeling results for 2011 February 14 20:35 UT, about 5 hr before the X-class flare. (a) Rastapped HMI vector magnetogram for the center region of AR 11158 as viewed from overhead. The vertical field (B_v) is plotted in the background; blue (red) arrows indicate the horizontal field (B_h) with a positive (negative) vertical component. Contours are plotted at ± 500 G. (b) Vertical current density (J_z) derived from 5 pixel Gaussian-smoothed vector magnetogram. Contours are for B_v , and are identical to (a). Part of the PIL is plotted as a thick cyan curve. (c) Image from AIA 171 Å band showing the corona magnetic structures. The dotted box in the center indicates the PCW of Figure 2(a). (d) Selected field lines from the NLFFF extrapolation plotted over a cutout from the vertical field map. The lines are color-coded by the vertical current density at their footpoints (see the color bar); red field lines correspond to strong current density. The white dotted box indicates the PCW of (a) and (b). The PCWs of (c) and (d) are identical, about 218×218 Mm², or $302'' \times 302''$. Features of interest are marked in each panel; see the text for details. See accompanying animation of the vector field data set for the entire 5 day period.

(An animation of this figure is available in the online journal.)

图 6. 4: 2011 年 2 月 14 日 20:35 UT 耀斑前 5 小时的观测与模型比较。(a)HMI 矢量磁图，(b)垂直电流密度，(c)AIA 171 Å图，(d)NLFFF 磁力线 [Movie](#)

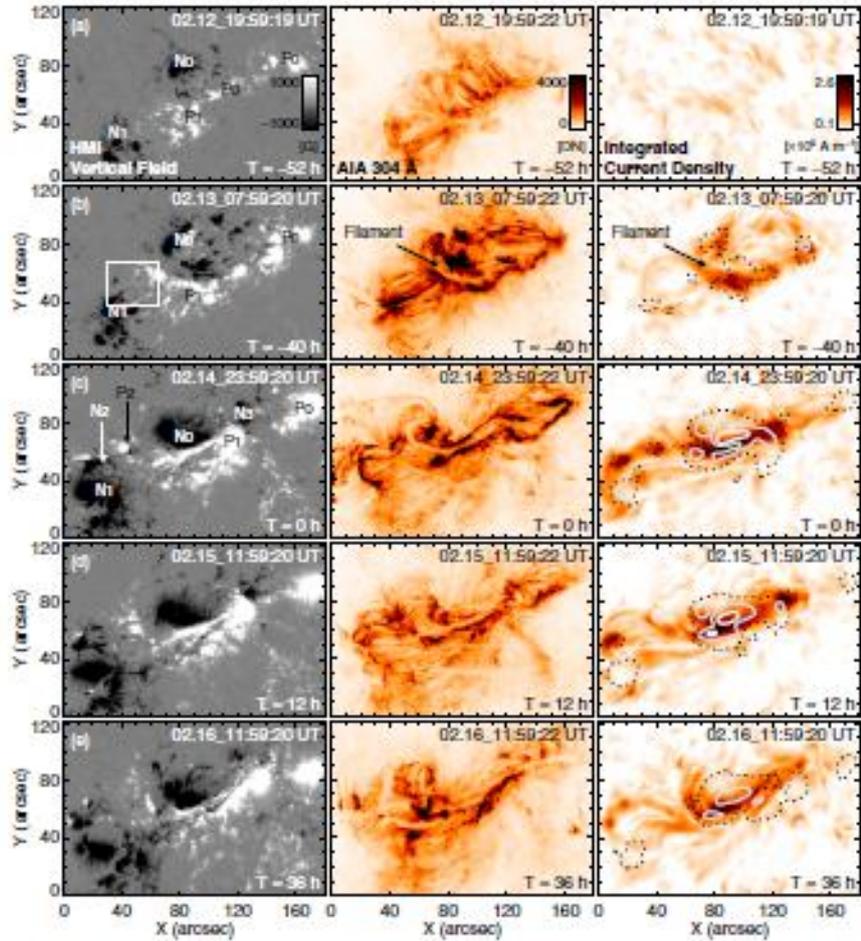


Figure 3. Five snapshots of the evolving AR11158. They are taken at about $T = -52$ h, -40 h, 0 h, 12 h, and 36 h, with February 13 00:00 UT as time 0. Left column: HMI B, as in native coordinates (as recorded by camera). Middle column: negative AIA 304 Å image showing chromosphere and transition region structures in which the AR filament is best discernible. Right column: vertically integrated current density from NLFFF extrapolation over the lowest 10 Mm. The thick solid, thin solid, and dotted contours are for similarly integrated free energy density at 80%, 50%, and 20% of the peak value for frame $T = 0$ h. Images are remapped back to the native coordinate for direct comparison of HMI and AIA observations. The box in (b) indicates the field of view of Figure 10 for a flux-emerging region. Features of interest are marked in some panels; see the text for details. An animation of the entire 5 day period is available in the online journal. (An animation and a color version of this figure are available in the online journal.)

图 6.5: AR11158 观测: HMI Bz (左)、AIA 304 (中) 及 NLFFF 计算的垂直电流积分 (右)

[Movie](#)

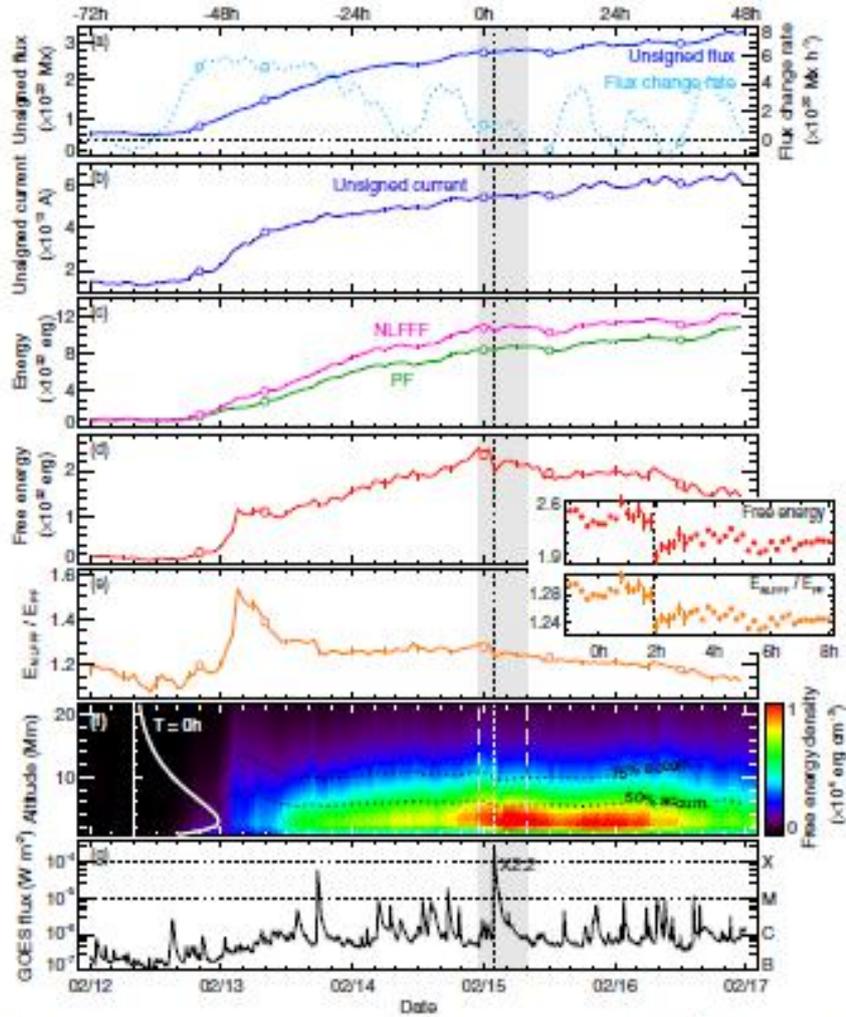


Figure 4. Evolution of magnetic energy and related quantities of AR 11158 over 5 days. (a) Total unsigned magnetic flux ($|\Phi|$) and 6-hr smoothed flux change rate ($d|\Phi|/dt$). (b) Total unsigned current ($|J|$). (c) Magnetic energy derived from the NLFFF and PF extrapolation (E_N and E_P). (d) Estimated magnetic free energy (E_f). (e) Ratio between the NLFFF and PF energy (E_N/E_P). (f) Time-altitude diagram of average magnetic free energy density in the AR center (PCV of Figure 5(c)). The dotted lines indicate the height below which the accumulated values reach 50% and 75% of the total. The curve on the left shows the height profile for $T = 0$ hr. (g) GOES 5 soft-X ray flux (1–8 Å channel). The 5 frames in Figure 3 are marked as circles. Flux and current are derived using only pixels with $|B_z|$ greater than 100 G. Error bars in (c)–(e) show the estimated effect of noise and are plotted every 6 hr, but are usually too small to be seen. Insets of (d) and (e) show results with a 12 minute cadence from –1 hr to 8 hr (shaded gray band). Error bars right below; and after the X-class flare in these insets are more visible. The vertical dotted lines indicate the peak time of the X-class flare at 1.5 hr.

图 6. 6: 磁能及参数演化

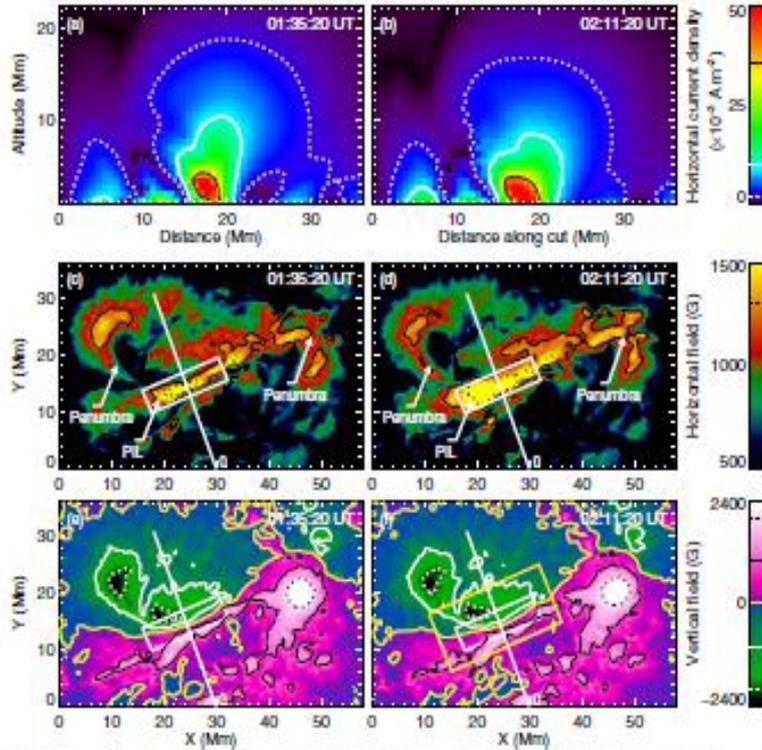


Figure 5. Rapid field changes at the photosphere and in the corona during the 2011 February 15 X-class flare. (a) J_h distribution on a vertical cross section as derived from NLFFF extrapolation, before the flare at 01:35:20 UT. Only the component perpendicular to the cross section is included. The location of the cross section is indicated in panels (c)–(f) as a long straight line. The dotted, dashed, and solid contours indicate values of 2, 10, and 36 mA m⁻², respectively. (b) Same as (a), for 02:11:20 UT after the flare. (c) Romapped B_h observed by HMI for 01:35:20 UT as viewed from overhead. The dotted (solid) lines show contours for 1600 G (1200 G). Places with significant field change are marked by arrows and boxes. (d) Same as (c), for 02:11:20 UT. (e) Romapped B_v at 01:35:20 UT. The dotted (solid) contours are for ± 2000 G (± 1000 G). (f) Same as (e), for 02:11:20 UT. The large yellow box indicates the region evaluated in Figure 9(d). (An animation and a color version of this figure are available in the online journal.)

图 6. 7: 水平电流密度 (上)、水平场 (中) 及垂直场(下) [movie](#)

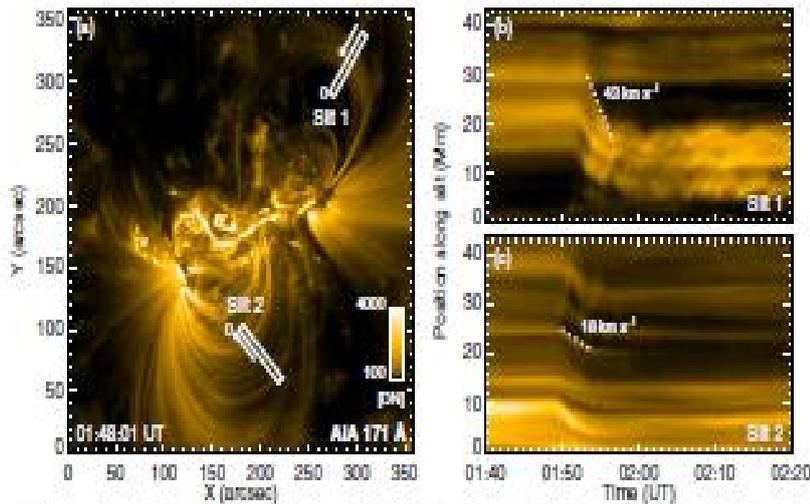


Figure 8. Observed EUV coronal loop retractions. (a) AIA 171 Å image at 01:48:01 UT on February 15, after the onset of flare. Two slits that are largely perpendicular to the loops are used to obtain the time–position diagrams in the following panels. Arrows along the slits indicate the approximate direction of the transverse motion. (b) Time–position diagram for slit 1 constructed by stacking a time sequence of co-aligned images taken from left to right. Only the images with the normal exposure time are used, resulting in a 24 s cadence. Images are co-aligned to sub-pixel accuracy. The dotted line shows an inward loop contraction pattern with a transverse speed of 43 km s⁻¹. The horizontal pattern in the upper half are from the features in the background. Loop oscillations are visible. (c) Same as (b), for slit 2. The dotted line shows a transverse speed of 18 km s⁻¹. Patterns of expanding loops also appear around 01:50 UT, moving from position 20 Mm toward 40 Mm. (An animation and a color version of this figure are available in the online journal.)

图 6. 8: AIA 171 Å EUV 冕环观测 [Movie](#)

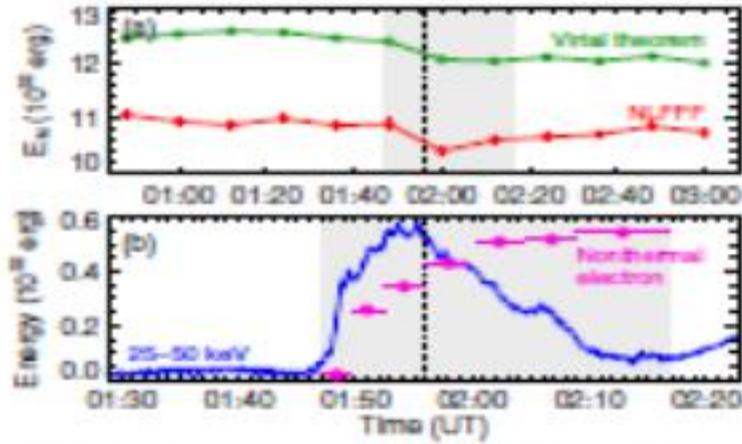


Figure 11. Estimation of flare energy release. (a) Magnetic energy estimated from the NLFFF extrapolation (same as Figure 4) and the magnetic virial theorem. The magnetic virial theorem is applied on a preprocessed lower boundary; the uncertainty is derived from a Monte Carlo approach. Most error bars are too small to be seen. The gray background indicates the period during which the nonthermal electron energy is fitted in the next panel. (b) Accumulated nonthermal electron energy derived from RHESSI HXR spectra using the thick-target model. Spectra for seven individual time intervals covering 01:44 UT to 02:17 UT (gray background) are fitted; the time range of each is noted by the horizontal bars. The HXR light curve in the 25–50 keV band is plotted in the background on a logarithmic scale. The vertical dotted line (01:56 UT) shows the XRR peak in GOES light curve.

图 6. 9: 耀斑能量释放 (a) 及非热电子能量 (b)

6.2.2. 2011 年 2 月 15 日 X2.2 耀斑、带、冕峰及物质抛射: MHD 通量绳模型

Schrijver 等 (2011, APJ, 738, 167) 分析了 2011 年 2 月 15 日 SDO/AIA 及 STEREO 观测到 X2.2 耀斑及向地全晕 CME。从 11158 活动区中心 δ 黑子群之间的剪切极性翻转线上方的通量绳结构可以看到膨胀环, 最终形成 CME 运动到日球内部。观测支持如下解释: 包括 EIT 波的这些特征是由环示踪的碰撞体, 被移动的波峰包围, 而不是波主导的扰动。爆发的侧面膨胀被限制在局部盔状流结构并停在相连的大规模区域边缘。AIA 观测显示等离子体加热发生在波峰内部, 利用 AIA 响应函数分析, 通过宁静太阳的波峰部分与绝热加热一致, 其它部分需要 MHD 模型暗示的焦耳耗散等额外加热。尽管该事件的体积膨胀远比真正的波膨胀明显, 他们还是讨论了在爆发区内及周围不同地磁环境如何导致这些特征。

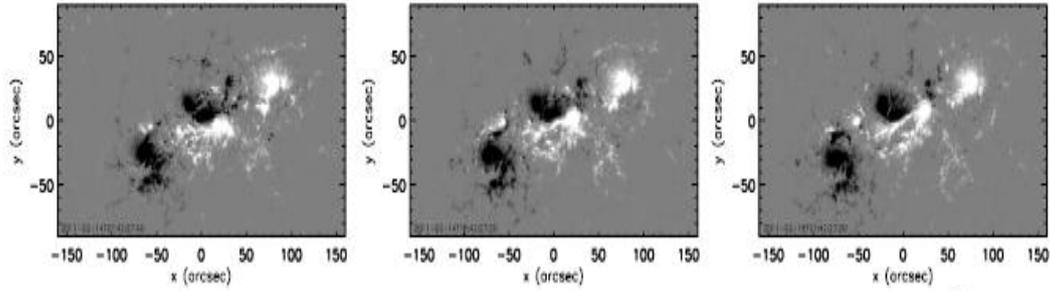


Figure 2. Sample HMI magnetograms of AR 11158 16, 8, and 0 h before the start of the X2.2 flare. The intensity scale saturates at $\pm 1500 \text{ Mx cm}^{-2}$. Movie 1 shows the evolution of the region over a 5D interval prior to and just after the flare. Compare with Figure 3 and Movie 3 for alignment of the magnetogram with the overlying coronal features. Movie 1 shows the HMI magnetogram sequence (640×360 pixels of 0.50 arcsec each) tracing the emergence and evolution of AR 11158 from 2011 February 10 14 UT to 2011 February 15 06 UT. The scale saturates at $\pm 1500 \text{ Mx cm}^{-2}$.

(An animation (Movie 1) of this figure is available in the online journal.)

图 6. 10: 2011 年 2 月 10 日 14 UT HMI 观测的 NOAA11158 耀斑前矢量磁图 [Movie](#)

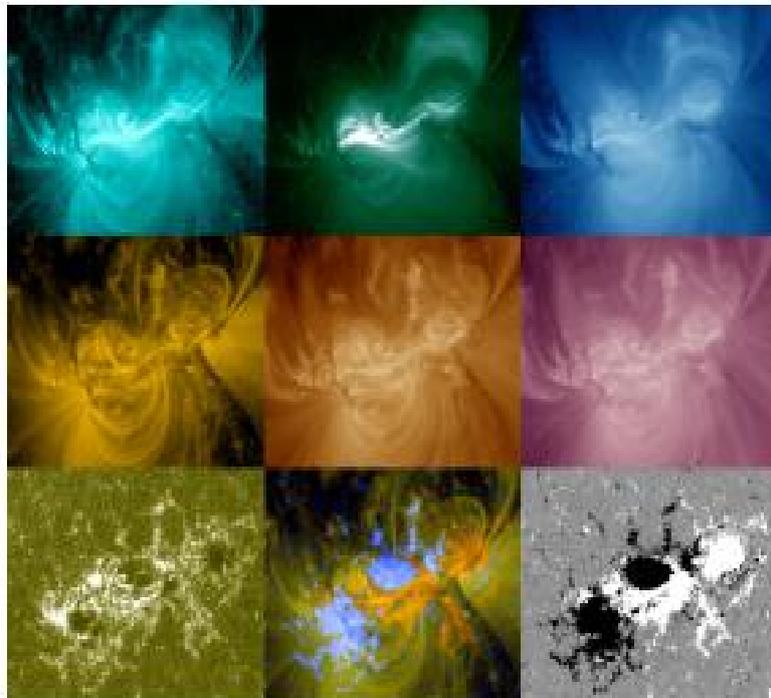


Figure 3. Composite of AIA images and (lower-right) an HMI magnetogram, all taken within 13 s from 2011 February 15 01:46:56 UT. Top row: the channels sensitive to high temperatures: 131, 94, and 335 Å. Center row: the channels sensitive to $\sim 1\text{--}2$ MK: 171, 193, and 211 Å. Bottom row: comparisons with lower atmosphere: 1600 Å channel, a blend of the 171 Å image with a line-of-sight magnetogram, and the HMI LOS magnetogram. The field of view of each panel extends over 400 pixels in the east-west direction or 210 Mm. Movie 3 shows the image sequence of composite of AIA images and (lower-right) an HMI magnetogram, showing frames at a 12 s cadence (and the nearest available HMI LOS magnetogram) starting at 2011 February 15 01:43:00 UT. Top row: an RGB blend of 94, 335, and 193 Å images next to the channels separately which are sensitive to relatively high temperatures (see Figure 1 for a comparison of response curves): 131, 94, and 335 Å. Center row: the channels sensitive to $\sim 1\text{--}2$ MK: 171, 193, and 211 Å, with the leftmost panel showing these as an RGB blend. Bottom row: comparisons with lower atmosphere: 1600 Å channel, a blend of the 171 Å image with an LOS magnetogram and the HMI LOS magnetogram. The FOV of each panel extends over 400 pixels in the east-west direction, or 210 Mm. The movie covers the time interval from 01:43 UT to 02:45 UT (compare with the 335 Å light curve in Figure 7).

(A color version and an animation (Movie 3) of this figure are available in the online journal.)

图 6. 11: AIA (131, 94, 及 335Å, 上)、(171, 193, 和 211Å, 中)、(1600Å, 下) 及 HMI (右下) 图 (2011 年 2 月 15 日 01:46:56 UT) [Movie](#)

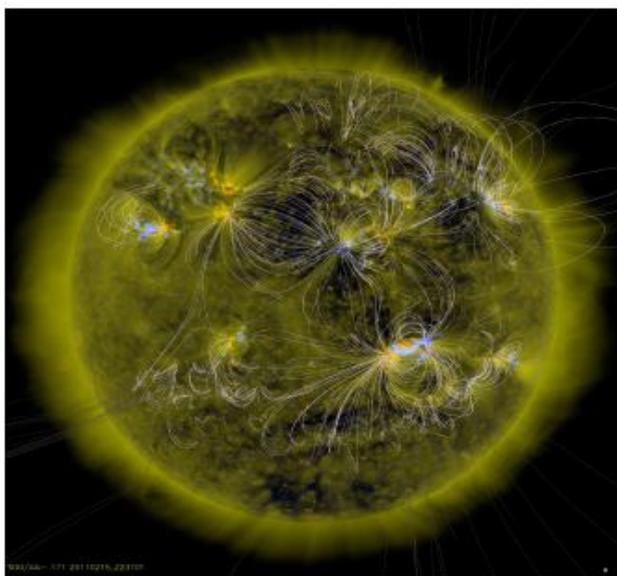


Figure 5. Potential field source surface field lines shown projected onto an SDO/AIA 171 Å image taken on 2011 February 15. (A color version of this figure is available in the online journal.)

图 6. 12: 势场源表面场线叠加在 SDO/AIA 171Å 图

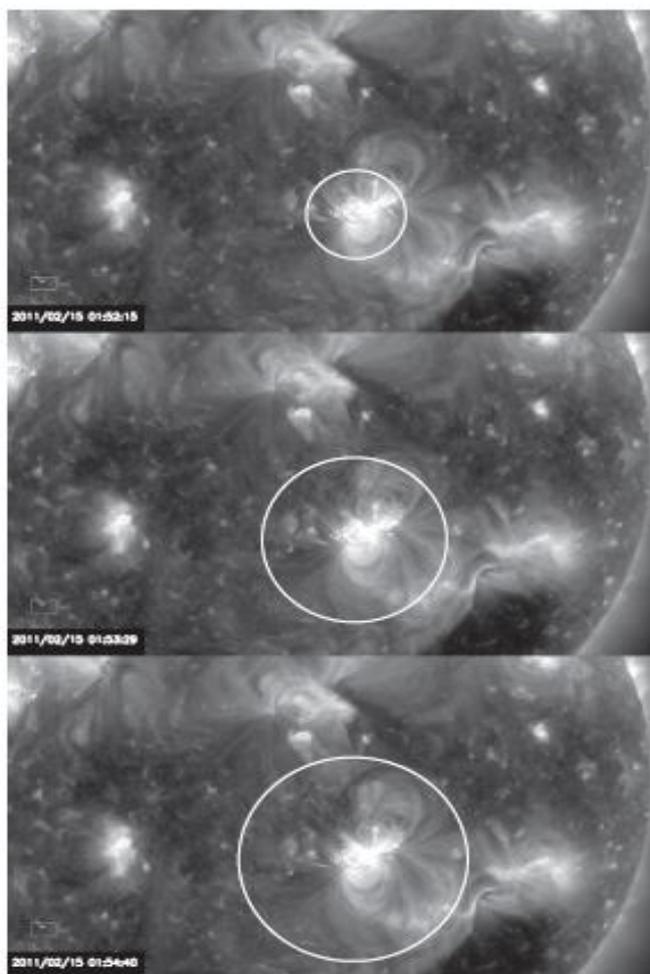


Figure 6. Composite of three SDO/AIA frames taken in the 211 Å channel. Circles outline approximately the envelope of the expanding loops (top) transitioning into an expanding front (bottom), not reflecting the anisotropy of this expansion. The field of view is shown as a rectangle on the clock face, with that face representing the solar disk. See Movie 1 for all 211 Å exposures taken between 01:46 UT and 02:08 UT on 2011 February 15. Movie 2 shows the image sequence in the SDO/AIA 211 Å channel showing the flaring region AR 11158, the expanding loops from its core, and the propagation of the coronal perturbation front associated with it. The movie runs from 01:46 UT to 02:08 UT on 2011 February 15. (An animation (Movie 2) of this figure is available in the online journal.)

图 6. 13: 2011 年 2 月 15 日 01:46 UT SDO/AIA 211Å图 [Movie](#)

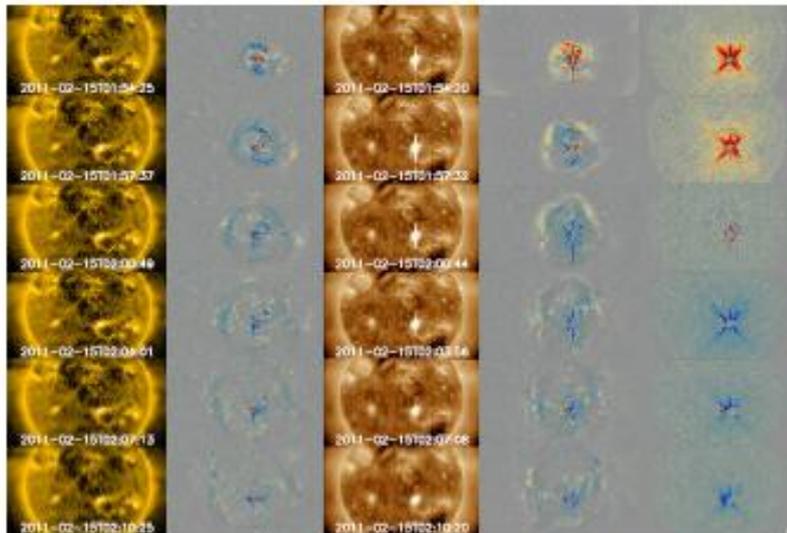


Figure 16. Composite of images in AIA's 171 and 193 Å channels (Columns 1 and 3) and the associated running difference images (Columns 2 and 4; compare Movie 4 and 5), and the running difference images in the 131 Å channel (Column 5; compare Movie 6). The running difference images (based on a temporal spacing of 96 s) are displayed as yellow to red for increasing brightening, and as light blue to dark blue for increasingly strong dimmings (see Figure 11). Movies 5, 6, and 7 show running difference movies for AIA's 171 Å, 193 Å, and 131 Å, channels, respectively for 2011 February 15 00-03 UT. Yellow to red indicate increasingly strong brightenings, light blue to dark blue increasingly strong dimmings. The images were smoothed over 3 pixels to reduce the noise and image pairs were used with a temporal spacing of 96 s; absolute difference can be estimated using Figure 11 with a multiplier of 11, 8.5, and 1.1 DN a^{-2} in movies 5, 6, and 7, respectively. Each image shows the full width of the AIA FOV (40 arcmin). Three stars for $I_{\text{tot}} - I_0$ show flux I . (Animations (Movie 5, Movie 6, Movie 7) of this figure are available in the online journal.)

图 6. 14: 2011 年 2 月 15 日 15 UT NOAA11158 活动区 AIA171、193 及 131Å 差分图

[Movie](#) [Mivie](#) [Movie](#)

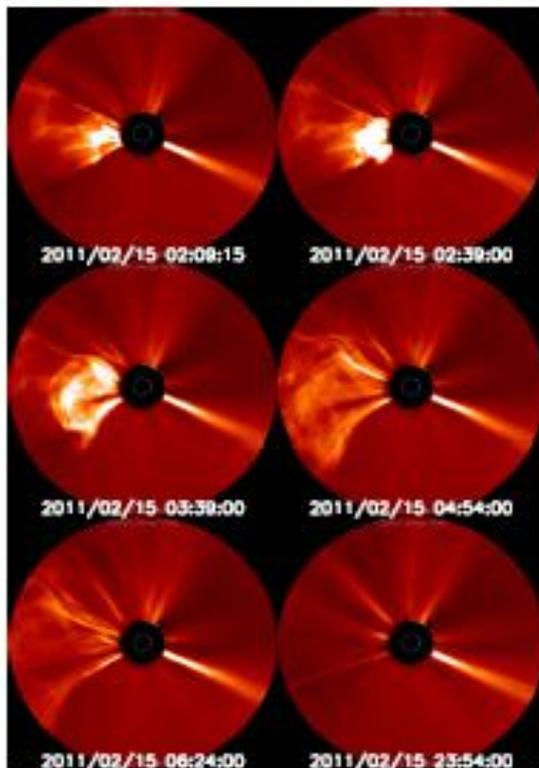


Figure 15. Composite of images taken by STEREO A/COR2 (times are shown on the images). Movies 8 and 9 show the STEREO A/COR2 and STEREO B/COR2 movies, respectively, for 2011 February 15. (A color version and animations (Movie 8, Movie 9) of this figure are available in the online journal.)

图 6. 15: 2011 年 2 月 15 日 STEREO A/COR2 及 STEREO B/COR2 观测到的 CME

[Movie](#) [Movie](#)

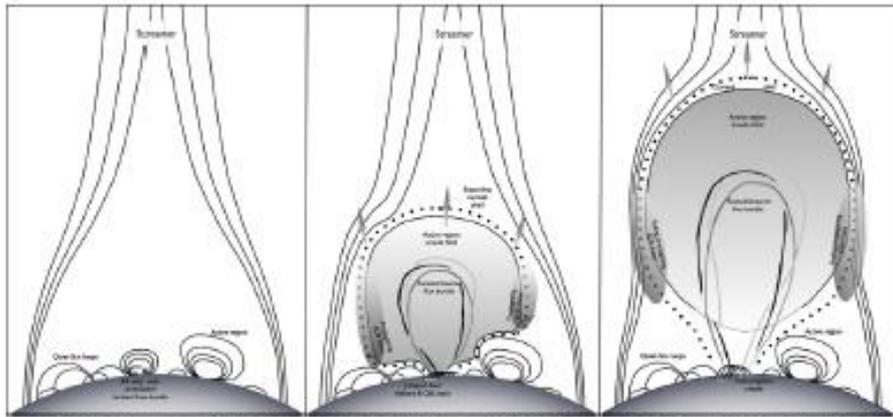


Figure 22. Sketch of the process involved in a coronal propagating front as discussed in this study, rendered in a substantially simplified geometry that captures only the essential characteristics. On the left is a rendering of the pre-eruptive state: an active region with a sheared and twisted flux rope bundle, with a neighboring active region, both surrounded by a carpet of quiet-Sun field of a variety of lengths and strengths, and beneath a cusp formed by closed field with field open into the heliosphere outside of it. In the center is a rendering with the eruption in progress: the shaded volume, containing the flux bundle and surrounding active-region field, is expanding rapidly, both in horizontal and vertical dimensions, affecting only the high regions of the strong-field environment of the active region. As the front moves up and out—visualized in the transition from the central to the right-hand panels—it disturbs the boundaries of the coronal cusp, as it must in order to reach the heliosphere. The expansion front is compressing and warming the surrounding field and plasma at the enveloping current shell, resulting in the appearance of a propagating front (schematically indicated by the shaded oval), which may manifest itself either as a brightening or as a dimming depending on the temperature of the plasma.

图 6. 16：日冕传播峰示意图

表 6. 1：耀斑的早期发展

Table 1
Phases in the Early Flare Development

Time (UT)	Note
01:44	<i>GOES</i> flare start.
01:45	Flare ribbons initiate. First loop expansion.
01:47–48	<i>J</i> -shaped ribbons form and brighten. Loop expansion accelerates.
01:48:18	Flare ribbons extend beyond central δ spot.
01:50:15	Ribbons reach into leading spot.
01:50–53	Expanding loops fade.
01:53–54	Expanding coronal front forms.
01:56	<i>GOES</i> flare peak. Ribbons reach maximum extent.

6.2.3. 光球磁场对 2011 年 2 月 15 日 X2.2 耀斑的响应

Wang 等 (2012, APJL, 745, L17) 利用 SDO/HMI 数据分析了 2011 年 2 月 15 日 X2.2 耀斑事件, 发现磁翻转线(PIL)的水平磁场快速 (30 minutes)且不可逆的增强 (~30%), 光球磁场变得更加剪切与倾斜。场演化与 S 型活动区的耀斑发生相关, 增强的面积位于两个色球耀斑带与初始共轭硬 X 射线足点之间, 在爆发之后, PIL 附近的磁力线更水平, 与脱缰 (tether-cutting) 重联新形成的下方场有关。

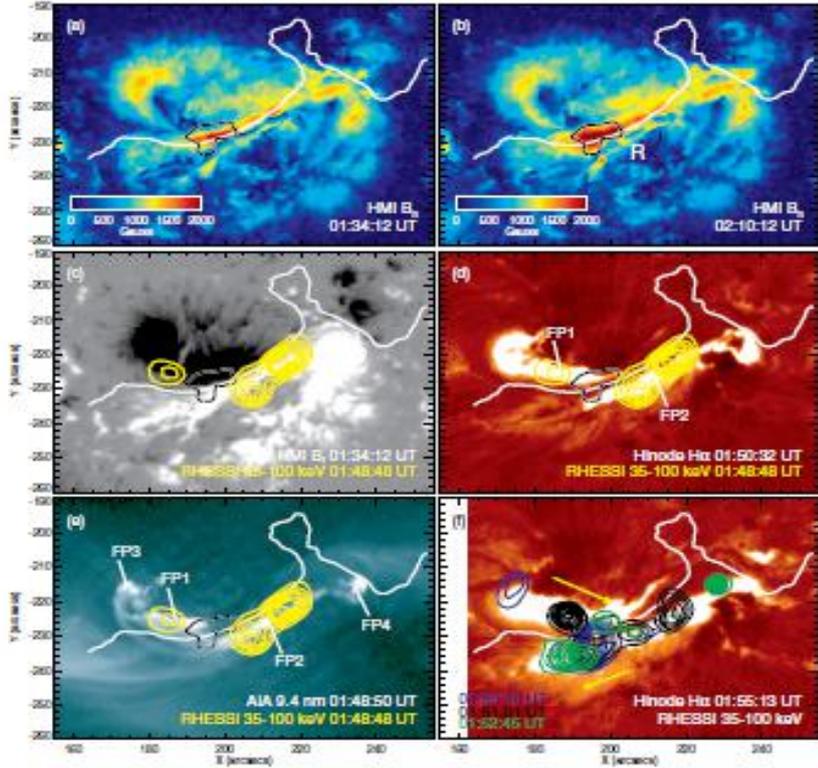


Figure 1. Preflare (a) and postflare (b) HMI B_h maps revealing the enhancement of horizontal field in a region R at the P.U. (white line) as enclosed by the white bordered line, which is defined based on the smoothed difference image of B_h . A postflare B_h map in (c) (scaled at ± 1 kG), the first available *Moderate* Hix image in (d), an AIA 94 Å image at the flare onset in (e), and an Hix image at the flare peak time in (f) are overlaid with contours (30%–90% of the maximum flux) denoting *RHESSI* PIXON images. The arrows in (f) indicate the direction of motion of the main HXR footpoints, as well as that of the chromospheric ribbons besides their separation.
 (A color version of this figure is available in the online journal.)

图 6. 17:耀斑前后 HMI 磁图

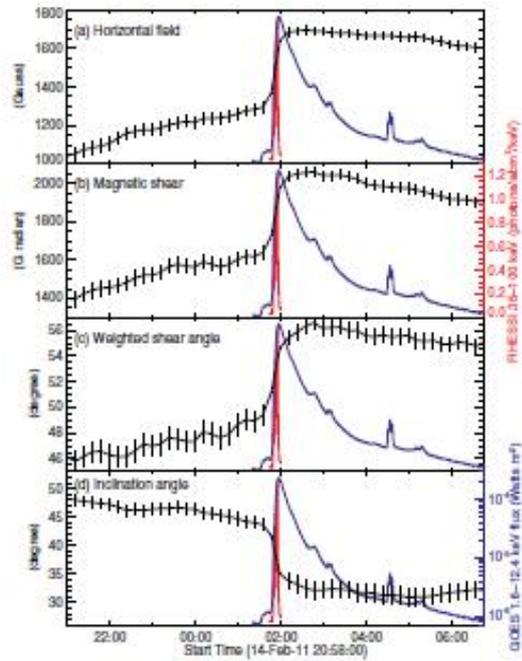


Figure 2. Temporal evolution of various magnetic properties of region R enclosed by the white bordered line in Figure 1, in comparison with the light curves of the *RHESSI* HXR flux in the 35–100 keV energy range (red) and *GOLF* flux in 1–8 Å (blue). The vertical error bars indicate 3 σ level. See Section 1 for details.
 (A color version of this figure is available in the online journal.)

图 6. 18:磁场参数时间演化

6.2.4. SDO/AIA 观测的冕环及活动区自动温度及辐射测量分析

Markus 等 (2013, Solar Phys, 283,5 - 30) 发展了一种数字编码用来自动分析 SDO/AIA 图像数据, 包括: i) 不同波段的对齐; ii) 自校准; iii) 自动产生微分辐射[DEM] 分布; iv) 活动区或小面积的 DEM 分布组合; v) 自动检测冕环; vi) 自动去除背景及对冕环的热分析, 对冕环温度、温度宽度、辐射量 [EM]、电子密度及环宽度进行统计。

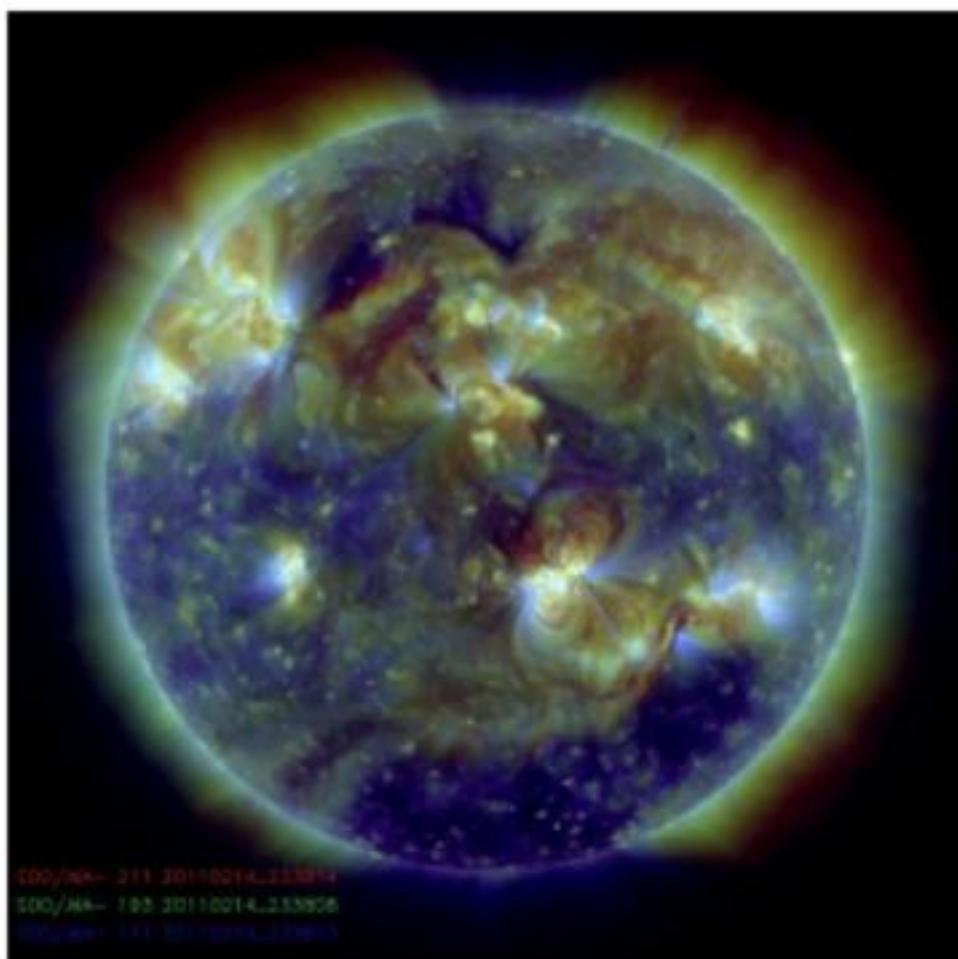


Figure 1 Composite triple-filter image of SDO/AIA consisting of a 211 Å (red), 193 Å (green), and 171 Å (blue) image, recorded on 14 February 2011 at 23:38 UT [courtesy of AIA team].

图 6. 19: SDO/AIA 211 Å (红)、193 Å (绿)及 171 Å(蓝)合成图 (2011 年 2 月 14 日 23:38 UT)

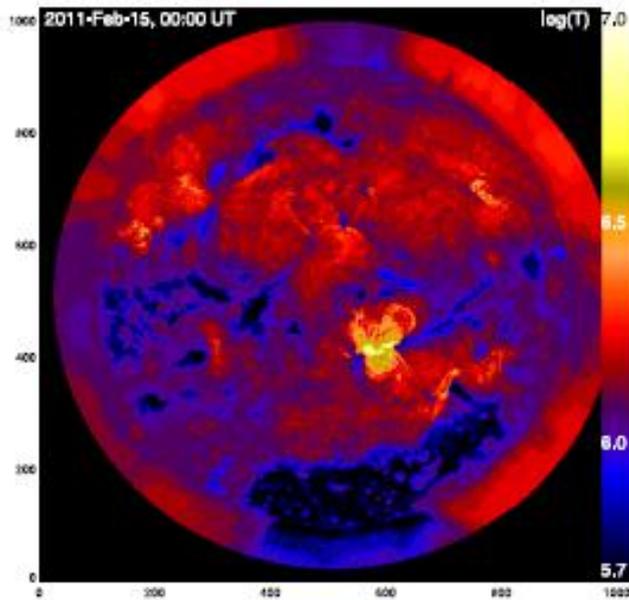


Figure 3. A temperature map calculated from the six AIA coronal filters recorded on 15 February 2011, at 00:00 UT. The temperature range is indicated in the vertical color bar on the right side, $\log(T) = 5.7 - 7.0$. The spatial resolution of the temperature map is $2.4''$, and each temperature value is calculated for an averaged macropixel with an area of 4×4 pixels.

图 6. 20: 温度分布图

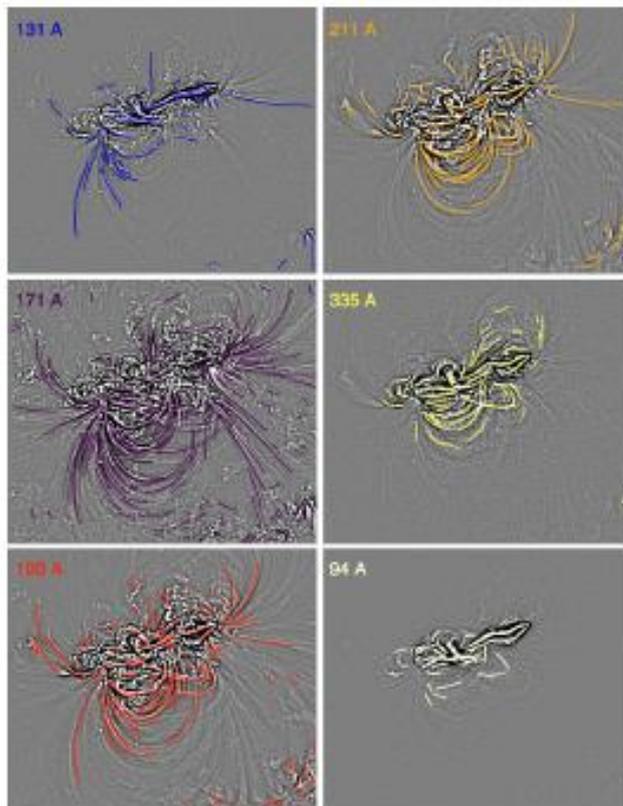


Figure 10. Automated loop tracings in the six AIA filters, overlaid on highpass-filtered images that were used to enhance and trace individual loops. The partial image covers the core of the active region as shown in Figures 7 and 8, including the pixel ranges of $x = 2050 - 2700$ and $y = 1300 - 1900$ of the original 4096×4096 image (Figure 1). The AIA pixel size is $0.6'' \approx 435$ km, and the field of view is 283 Mm \times 261 Mm.

图 6. 21: 自动环跟踪

6.2.5. 脱缠 (TETHER-CUTTING) 重联及磁内爆之后光球磁场的快速变化

Liu 等 (2012, APJL, 745, L4) 用线性无力场 (NLFFF) 方法分析了 HMI 观测到的 NOAA 11158 活动区 M6.6 耀斑期间磁场的快速变化, SDO/HMI 探测到的快速变化位于磁 S 型中心的紧致区, 平均水平磁场强度增加了 28%。该区域位于色球起始强 UV 和硬 X 射线源之间, 与 NLFFF 模型 S 型中心足点重合。NLFFF 模型还显示强日冕电流集中在该区域上方, 在 S 型爆发之后, 日冕电流系统经历了明显的向下塌缩。这些结果支持产生耀斑的 tether-cutting 重联及由能量释放导致的日冕场内爆。

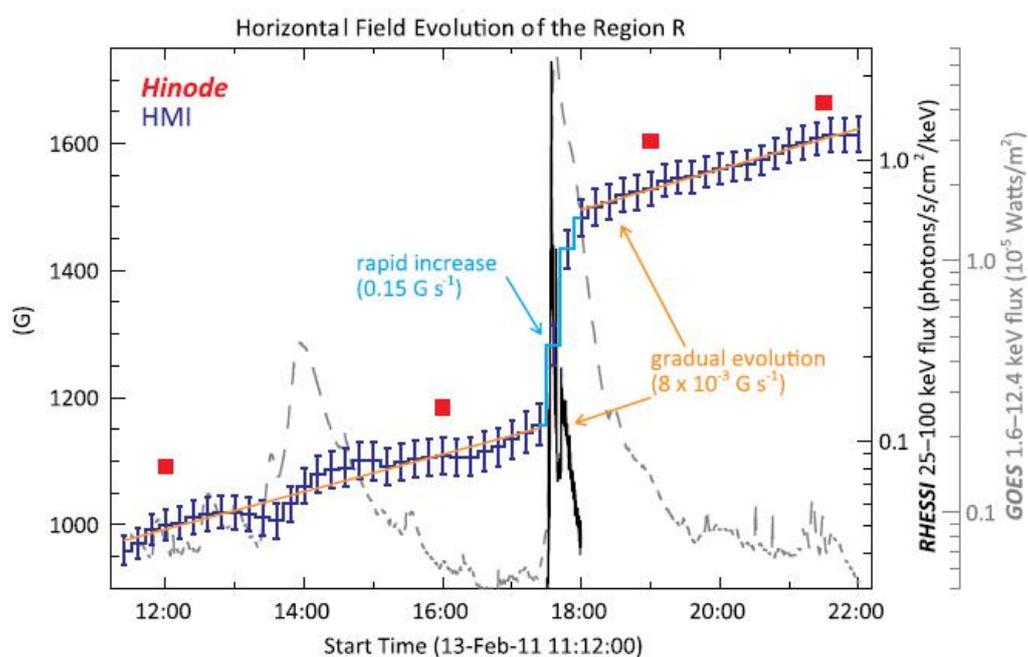


Figure 2. Temporal evolution of $\langle B_h \rangle$ of the region R in Figure 1, in comparison with the flare light curves of soft and hard X-rays. The mean error of B_h of the region R at each time instance measured by HMI is plotted as error bars. The error estimates for *Hinode* data are currently not usable (see footnote 6). (A color version of this figure is available in the online journal.)

图 6. 22: 水平磁场演化

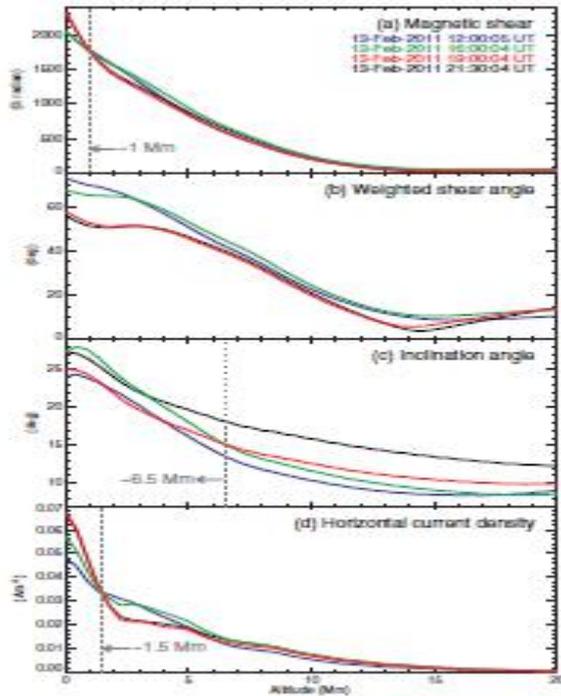


Figure 3. (β), S , $\langle \beta \rangle$, and J_h of the region R in Figure 1 as a function of altitude with a step size of ~ 0.46 Mm, at four times of *WIND* scans. (A color version of this figure is available in the online journal.)

图 6. 23: 磁剪切、剪切角、倾斜角及水平电流密度演化

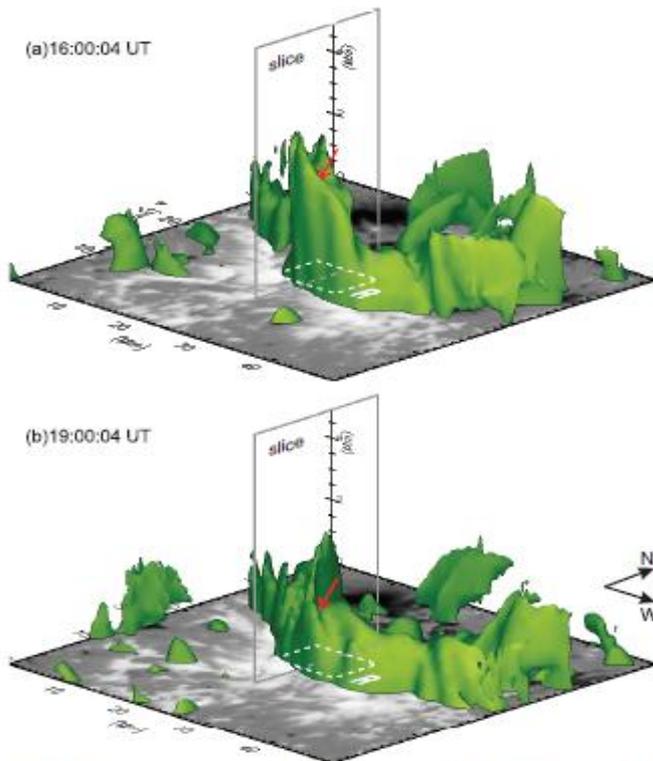


Figure 5. Isosurfaces of $J_h = 0.03 \text{ A m}^{-2}$ viewed from 30° relative to the horizontal plane and 45° clockwise about the vertical direction. The slice is the same as used in Figure 4.

(A color version of this figure is available in the online journal.)

图 6. 24: 水平电流等值面

6.2.6. 六个大中性线耀斑光球磁场与洛伦兹力矢量的突变

Petrie(2012, APJ, 759, 50)分析了 SDO/HMI 观测的四个活动区 NOAA 11158, 11166, 11283 和 11429 产生的六个大耀斑光球磁场突变的时空及时间变化。在六个耀斑期间, 中性线场矢量变得更强、更水平, 几乎都是由与中性线平行的水平场分量拉伸的结果。耀斑前中性线场比势场线更垂直, 在耀斑期间突然塌缩且永久地靠近势场倾角, 说明与非势场倾角相关的磁张力释放在大耀斑期间起了重要作用。与参考势场的剪切角并没有显示这种形态, 说明耀斑过程并没有缓解与光球磁剪切相关的磁张力。与耀斑前相比, 塌缩场更倾向于与中性线对齐。在耀斑期间, 垂直洛伦兹力由一个大的、突然的、永久的向下变化, 与环塌缩一致。水平洛伦兹力在中性线两侧以相反的方向场中性线平行, 是耀斑期间场收缩的特征。耀斑对场倾角比剪切更大的影响可由光球线捆 (line-tying) 解释。

表 6. 2: 六个耀斑参数

Table 1
Flares Studied in This Paper

Date (UT)	GOES Start Time (UT)	GOES Peak Time (UT)	GOES End Time (UT)	GOES Class	NOAA Number	Location on Disk
2011 Feb 13	1728	1738	1747	M6.6	11158	S20E05
2011 Feb 15	0144	0156	0206	X2.2	11158	S20W10
2011 Mar 9	2313	2323	2329	X1.5	11166	N08W11
2011 Sep 6	2212	2220	2224	X2.1	11283	N13W18
2011 Sep 7	2232	2238	2244	X1.8	11283	N14W31
2012 Mar 7	0002	0024	0040	X5.4	11429	N18E31

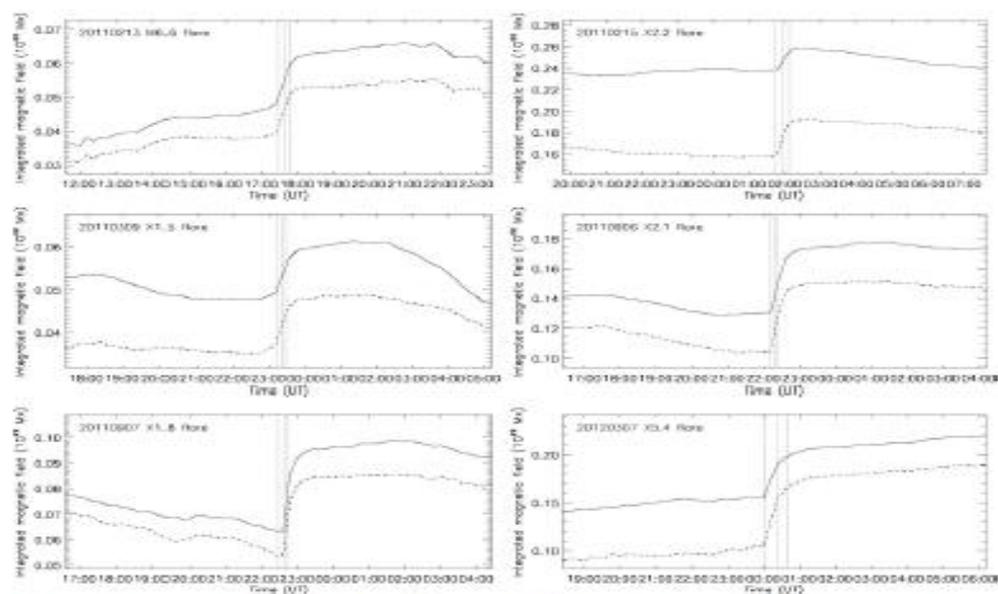


Figure 3. Shown here are the integrated magnetic field strength B_{int}^{tot} (solid lines) and B_{int}^{hor} (dashed lines) near each neutral line plotted against time. The areas of integration are indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.

图 6. 25: 中性线附近积分磁场强度 (实线) 与水平磁场的演化

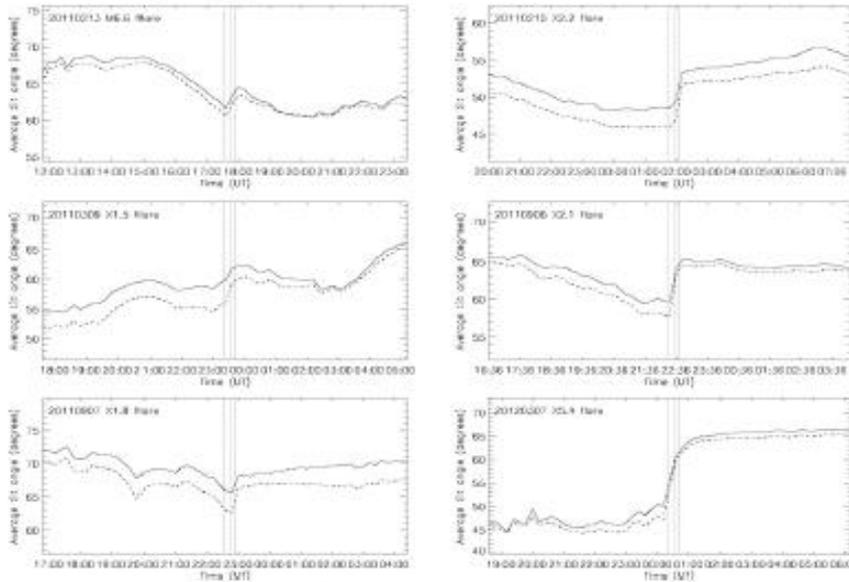


Figure 7. Shown here are the average tilt angles (solid lines) and the field-weighted average tilt angles (dashed lines) near each neutral line plotted against time. These angles are averaged over the areas of integration indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.

图 6. 26：平均剪切角演化

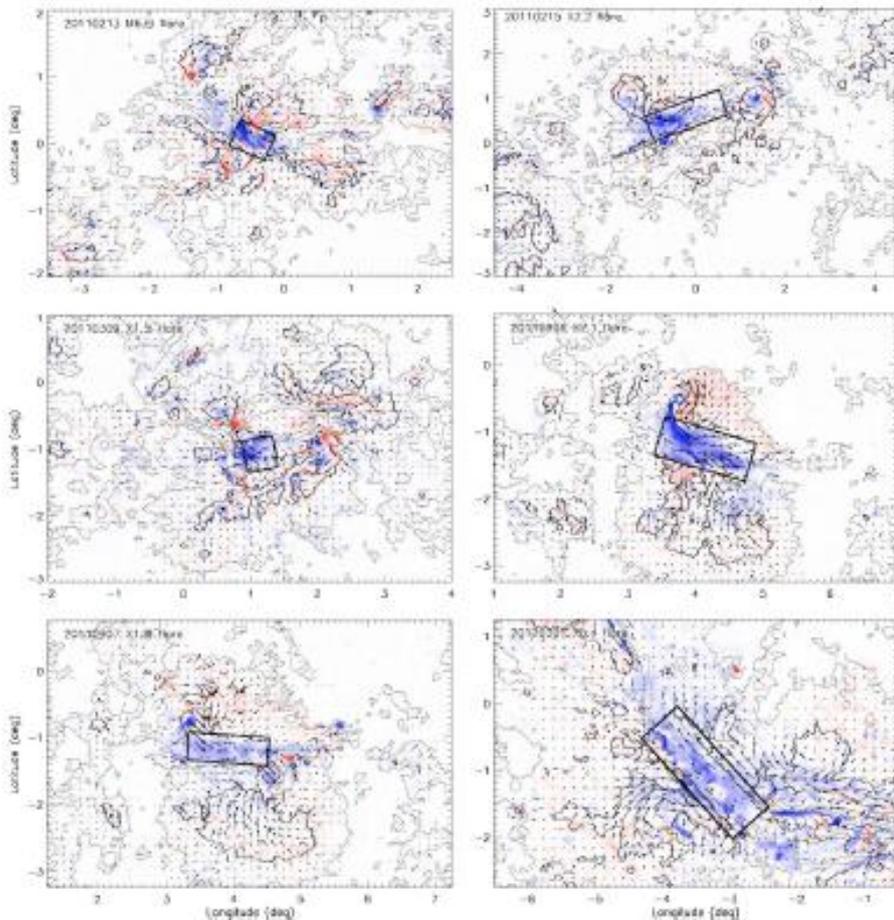


Figure 13. Lorentz force vector changes during each flare. The vertical component F_z is indicated by the color scale and the horizontal components by the arrows with saturation values 10^8 dynes cm^{-2} for the color scale and 2.5×10^8 dynes cm^{-2} for the arrows. Red/blue coloring represents positive/negative (upward/downward) Lorentz force change. The black rectangles mark the regions of major field change near the neutral lines. The solid and dotted contours indicate strong ($|B_z| > 1000$ G) and quiet strong ($|B_z| > 100$ G) fields, respectively.

图 6. 27：洛伦兹力矢量变化

6.2.7. 2011年2月15日 X2.2 耀斑期间日冕和光球内磁场塌缩证据：SDO/AIA 和 HMI 观测

Gosain (2012, APJ, 749, 85) 用 SDO/HMI 数据分析了 NOAA 11158 活动区冕环的演化，在该事件中识别出了冕环动力行为三个明显的相位：(1)慢上升相位：耀斑前环顶慢的上升运动，(2)塌缩相：环顶的突然收缩，较低环塌缩的比较高的环要早；(3)震动相：在塌缩相之后，环显示在不同周期的全球 kink 震动周期随环高度的减少而减少。这些冕环震动的周期用来估计冕环内的场强。还研究了靠近极性翻转线 (PIL) 的光球变化，耀斑后纵向磁图在沿着 PIL 相干斑上方显示磁通阶跃式的永久减少现象。通过分析该斑上方 HMI Stokes 参量，发现耀斑后 V 分量系统地减少，而 Q 及 U 分量增加。这些观测提示耀斑之后，靠近 PIL 的磁场形状变得更加水平。此外，通过对磁场倾角定量分析，发现场线朝 PIL 向内塌缩 10 度。这些结果与“日冕内爆”一致。

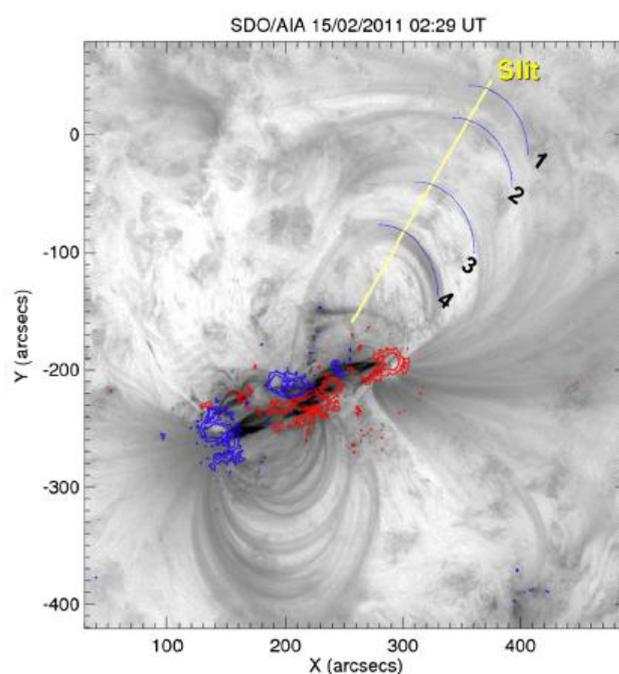


Figure 1. Inverted color map of active region NOAA 11158 observed in Fe ix 171 Å wavelength by the SDO/AIA instrument during 02:29 UT on 2011 February 15. The loops marked 1–4 are studied for temporal evolution and are highlighted by blue curved line segments. The line contours at 500 and 1000 G levels of the longitudinal magnetic field observed by the SDO/HMI instrument are overlaid in blue (red) colors, representing negative (positive) polarity, respectively. The yellow line marks the position of the artificial slit that is placed to sample the dynamics of the apex of the loops. The spacetime diagram corresponding to the slit is shown in Figure 2.

(An animation and a color version of this figure are available in the online journal.)

图 6. 28：2011 年 2 月 15 日 02:29 UT SDO/AIA Fe ix 171Å 观测到的 NOAA11158 活动区

[Movie](#)

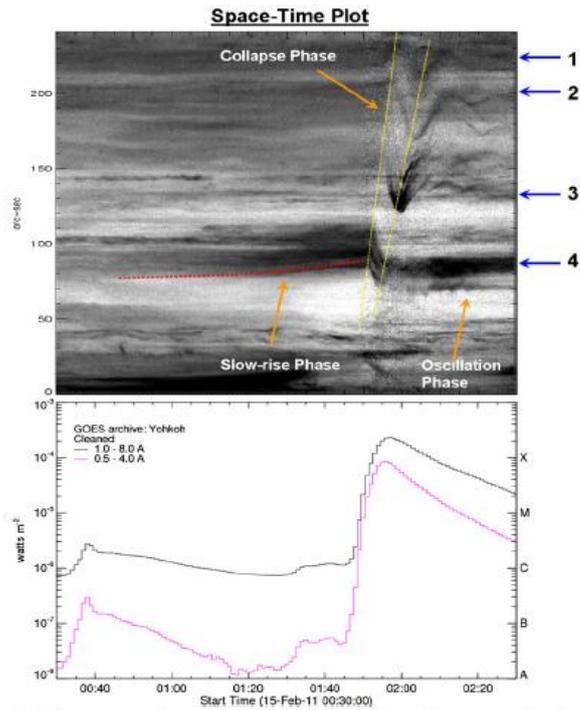


Figure 2. Top panel shows the spacetime diagram corresponding to the slit marked in Figure 1. The positions corresponding to loops 1–4 are marked on the right side. The three phases of evolution discussed in the text are marked in the figure and indicated by arrows. The bottom panel shows the soft X-ray light curve observed by the *GOES* satellite during the same time interval. (A color version of this figure is available in the online journal.)

图 6. 29: 空间-时间图 (上) 及 GOES X 射线图 (下)

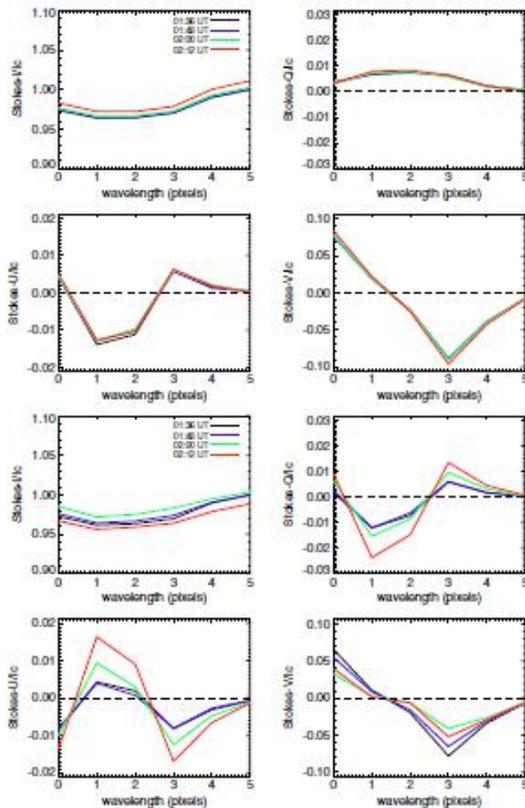


Figure 5. Top (bottom) four plots show the evolution of the mean Stokes profiles (normalized to continuum intensity, I_c) inside box "1" (box "2") marked in the top panel of Figure 3. The four sets of Stokes I/I_c , Q/I_c , U/I_c , and V/I_c profiles shows in different colors correspond to pre-flare time interval, 01:36–01:48 (black and blue curves), and post-flare time interval, 02:00 and 02:12 UT (red and green curves). (A color version of this figure is available in the online journal.)

图 6. 30: Stokes 参量变化

6.2.8. NOAA 11158 活动区旋转黑子的作用

Vemareddy 等(2012, APJ, 761, 60)利用 SDO/HMI 及 AIA 数据分析了 NOAA 11158 活动区与表征非势性的各种物理参数演化相关的旋转黑子的作用,发现该活动区由两个大旋转黑子组成,一个与易于产生耀斑的区域相连,另一个与 CME 相连。空时图显示黑子存在峰值旋转速度,与大爆发事件重合。Twist 参数的时间轮廓,即平均剪切角及螺度注入率与易于产生 CME 区域的黑子旋转轮廓对应很好,证明黑子旋转运动引起磁场非势性。在光球层由维力理论计算出的平均自由能清楚地显示在耀斑初始阶跃减少,证明耀斑前储存在通量浮现及运动中间歇性能量释放。螺度注入分布在与 CME 相关的区域是均匀的,而在与耀斑相关的区域则不是且常改变符号。本研究提出了一个清楚图像,在通过螺度与扭曲注入提升活动区磁非势性方面,通量的自行与旋转运动起到了显著的作用。

表 6. 3: NOAA11158 活动区耀斑与 CME

Table 1 List of Flares and CMEs			
AR (NOAA)	Date (dd/mm/yyyy)	Flares Magnitude(Time UT)	CMEs (Time UT)
11158	13/02/2011	C1.1(12:36), C4.7(13:44), M6.6(17:28)	21:30, 23:30
	14/02/2011	C1.6(02:35), C8.3(04:29), C6.6(06:51)	02:40, 07:00, 12:50
		C1.8(08:38), C1.7(11:51), C9.4(12:41)	17:30, 19:20
		C7.0(13:47), M2.2(17:20), C6.6(19:23)	
	15/02/2011	C1.2(23:14), C2.7(23:40)	
		C2.7(00:31), X2.2(01:44), C4.8(04:27)	00:40, 02:00, 03:00
		C1.0(10:02), C4.8(14:32), C1.7(18:07)	04:30, 05:00, 09:00
		C6.6(19:30), C1.3(22:49)	

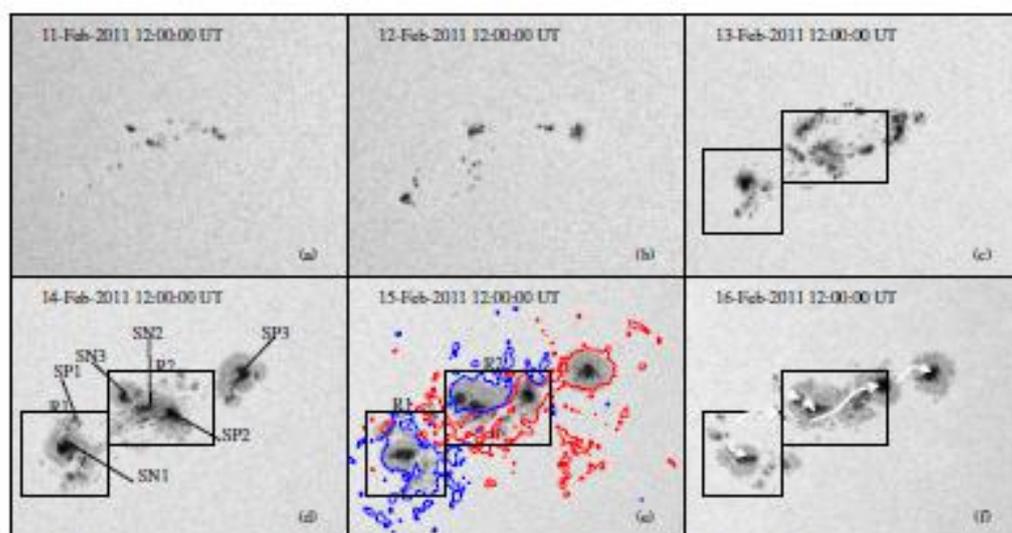


Figure 1. HMI intensity images showing the evolution of AR NOAA 11158 during a six-day time period. The main sunspots are labeled SP/N* in (d) and the LOS magnetic field contours are overlaid in red (blue) at 150(-150) G levels in panel (e) (also in subsequent figures unless specified). Proper motions of individual sunspots are traced along the arrowed curves as in panel (f). The two rectangular boxes mark the selected sub-regions R1 and R2 for further study. (A color version of this figure is available in the online journal.)

图 6. 31: NOAA 11158HMI 强度在六天的演化

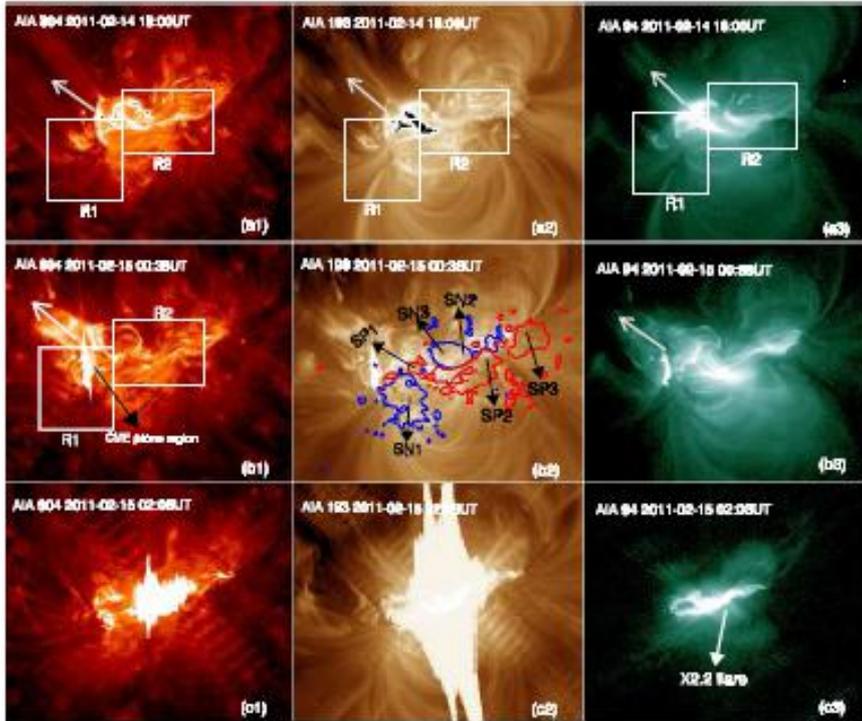


Figure 2. Coronal activity observed during the evolution of the AR in AIA wavelengths. (a1–a3) A mass ejection (white arrow) from R1 that eventually formed in to a CME on 2011 February 14 at 18:00 UT. (b1–b3) Another mass ejection observed on 2011 February 15 at 00:36 UT from the same location. (c1) Bright coronal streamer soon during the X2.2 flare, saturating the 193 Å detector (c2) and the twisted flux ropes along the polarity inversion line as seen in 94 Å (c3). (A color version of this figure is available in the online journal.)

图 6. 32: 活动区的日冕活动

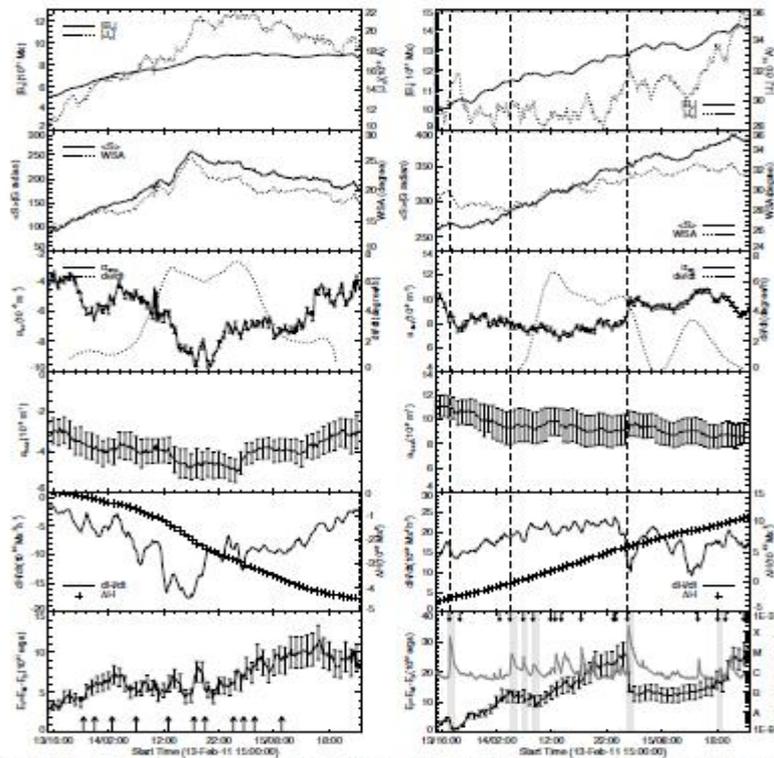


Figure 6. Temporal evolution of various physical parameters characterizing the non-potentiality in sub-regions R1 (left column) and R2 (right column). Arrows in the lower most panel of the left column mark the CME lifetimes while those in the right column correspond to the GOES-15 flares. The three major flares are marked by dashed vertical lines in all panels on the right column, and the shaded vertical bars indicate the release of free energy in step with the onset of flares. Note that all the listed parameters B_z , v_{shear} , average shear $\langle \dot{\phi} \rangle$, and $d\dot{\phi}/dt$ have clear correspondence to the rotational profile of the sunspot SN1, implying that sunspot rotation has a direct role in increasing the non-potentiality in sub-region R1.

图 6. 33: 表征非势性物理参数的演化

6.2.9. NOAA 11158 活动区相对磁螺度与电流螺度的演化

Jing 等 (2012, APJL, 752, L9) 分析了 NOAA 11158 活动区 2011 年 2 月从 2 日到 16 日磁螺度及电流螺度的时间演化, SDO/HMI 光球矢量磁场用作非线性无力场假设日冕外推的边界条件, 构建了一个时间-高度图, 电流螺度密度的高度分布是时间的函数, 图中清楚地显示 X2.2 耀斑之前两天内电流螺度密度向上传播, 传播与进入到光球的磁浮现同时, 及 X2.2 耀斑的能量逐渐积累。相对磁螺度的时间轮廓显示单调上升, 而在耀斑前由升降变化, 这种形态明显地存在于磁螺度中而没有存在于磁通量中。

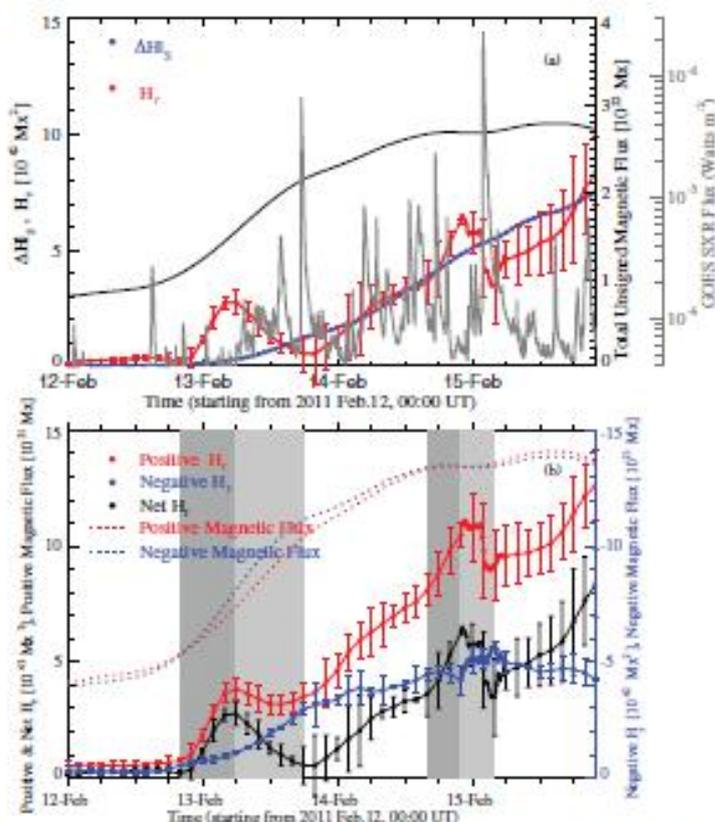


Figure 5. Temporal variations of magnetic helicity. (a) H_z (red dots), ΔH_z (blue dots), total unsigned magnetic flux (black) and GOES soft X-ray 1-8 Å flux (gray). The uncertainty in H_z is indicated by the error bars. The uncertainty in ΔH_z is generally 0.9% that is too small to be plotted. (b) total positive/negative/net helicity (red/blue/black dots) integrated over the volume, and total positive/negative photospheric magnetic flux (red/blue dashed curves) integrated over the PCN. The dark- and light-gray areas, respectively, mark the increasing and decreasing phase of two H_z bumps prior to two major flares. (A color version of this figure is available in the online journal.)

图 6. 34: 磁螺度时间变化

6.2.10. 与 2011 年 2 月 15 日 X2.2 耀斑相关的快速黑子旋转

江云春等 (2012, APJ, 744, 50) 利用 Hinode/SOT、SDO/HMI、SDO/AIA、SDO/XRT、SOHO/LASCO 等数据, 分析了 2011 年 2 月 15 日 11158 活动区黑子演化, 活动区由 4 个浮现的偶极场构成, 造成复杂的黑子运动, 前面的偶极黑子运动最快, 不仅通过另一偶极后随端, 从而引起剪切运动, 而且还与同极性的黑子混合形成单一的大本影。这样导致形成一个 S 形状的 δ 黑子, 在其上形成 EUV 暗条通道和 S 形态, 进而爆发产生耀斑。耀斑前 20 小时, 随着顺时针 (CW) 螺旋半影暗条形态的发展, 混合的黑子开始快速绕本影中心顺时针旋转。旋转持续整个耀斑期间但在耀斑结束之后 1 小时突然停止, 且保持扭曲半影暗条形状。运动的黑子还引起了连续通量对消, 在耀斑前 100 分钟, 其外部半影与小反极性黑子之间碰撞。当剪切与旋转运动是耀斑能量及螺度注入的主要贡献者时, 对消与碰撞可能起到引爆者作用。

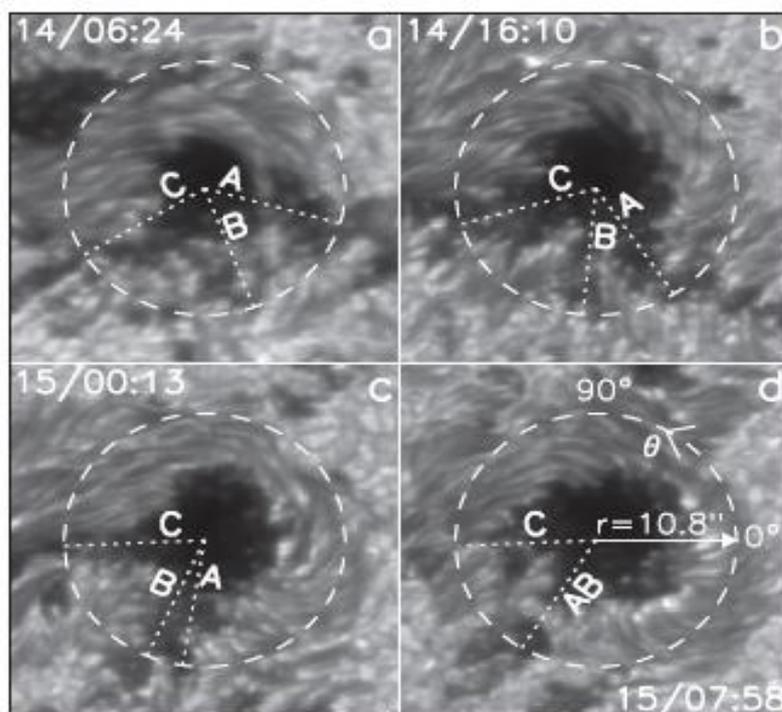


Figure 3. *Hinode* G-band images centered at p2's varying center. Three penumbral features, "A," "B," and "C," show clear CW rotation, along with the development of CW spiral pattern of p2's penumbral filaments. The dashed circles, with a radius of $10''.8$ from p2's center, indicate the location of the time slice shown in Figure 4. The r - θ polar coordinate system for uncurling the rotating p2 is shown in (d). The FOV is $30'' \times 30''$.

图 6. 35: Hinode G 观测清楚地显示半影特征 A、B、C 的顺时针旋转

6.2.11. 具有日冕零点的四极磁场中的非径向爆发

孙旭东等 (Sun, 2012, APJ, 757, 149) 利用 SDO/AIA、SDO/HMI、Hinode/SOT、Hinode/XRT、STEREO、GOES 等数据, 报道了 NOAA11158 活动区一个同源非径向爆发事件, 被局部磁场强烈调制, 在复杂黑子中浮现了一个小偶极子, 跟着产生了一个四极通量系统。从非线性无力场外推看到, 快速剪切偶极子仅仅在一天就积累了活动区 10% 的自由能量, 而其磁通仅仅占 5%。在爆发期间, 喷出的等离子体高度倾斜, 与径向夹角超过 60 度, 形成了一个喷气形状、到 Y 型结构。磁场外推显示与日冕零点复杂的磁连接, 以利于不同通量分量与四极系统的重联。实际上, 耀斑带大部分同时亮, 日冕重联出现零点附近。

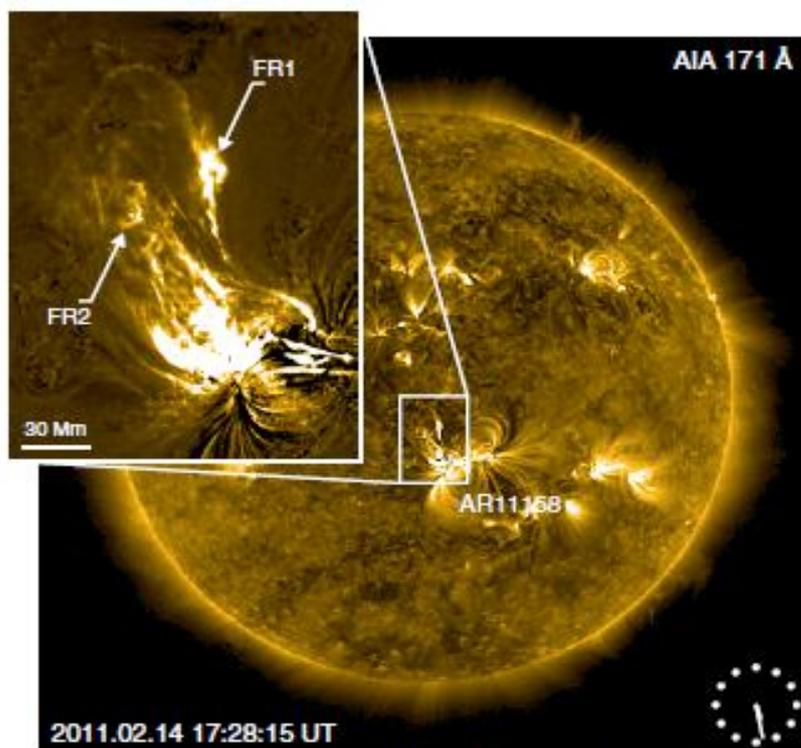


Figure 1. Full-disk, unsharp masked AIA 171 Å image at 17:28:15 UT on 2011 February 14 showing the non-radial eruption. Inset shows the enhanced image of the ejecta. The two flux-rope-like structures with a shared eastern footpoint are marked as FR1 and FR2. Animation of a 20 hr interval shows at least five similar eruptions.

(An animation and a color version of this figure are available in the online journal.)

图 6. 36: 2011 年 2 月 14 日 17:28:15 UT AIA 171Å 显示 NOAA11158 活动区非径向爆发

[Movie](#)

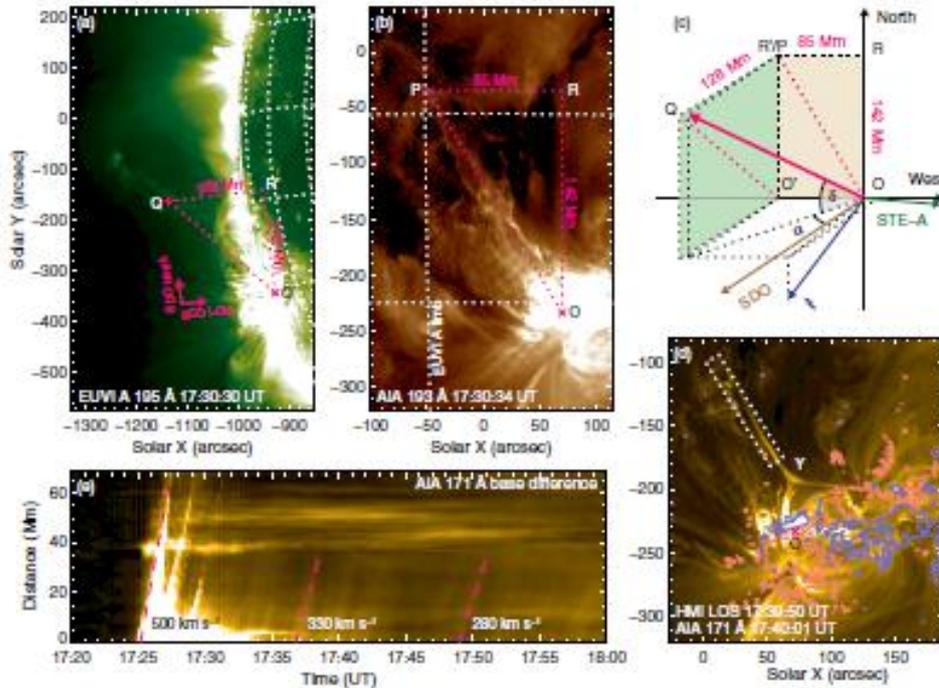


Figure 2. Geometry of the non-radial eruption. O and C' mark the eruption site. (a) SECCHI EUVI 195 Å image from STEREO-A, about 87° ahead of SDO. Due to the tilt of the solar rotational axis, the SDO and STEREO north are offset by 6°. (b) AIA 193 Å image of the same ejection, taken 4 s later than (a). The projected N-S length of the ejection (JOR) is identical to that in (a) (JOVR), where OR and OVR represent the projection of line segments OP and OQ in the N-S direction in SDO's plane of sky, respectively. The scales of (a) and (b) are different in order to better show the features of interest. (c) Schematic diagram explaining the determination of the ejection's geometry. SDO's west, north, and LOS directions are taken as the x-, y-, and z-axis. The pink arrow represents the ejection; its projected shape viewed from EUVI and AIA are shown as pink dashed lines on green and brown planes. The local radial vector is about W13894 to L426. The inclination δ is about 43°, azimuth α about 34°. See Section 3 for details. (d) AIA 171 Å image of the post-eruption AR; Y marks the top of the cap and the base of the spine. The boxed region is used to construct panel (e). Purple/pink contours are for HMI LOS field at ± 200 G. (e) Space-time diagram showing the speed of ejection and jet. Three dashed lines (starting near 17:25, 17:36, and 17:49 UT) indicate projected speeds of 500, 330, and 280 km s^{-1} , respectively. Panels (a), (b), and (d) are displayed on a square-root scale. (An animation of this figure is available in the online journal.)

图 6. 37: 非径向爆发的几何形状, (a) STEREO-A SECCHI EUVI 195Å 图, (b) AIA 193Å图, (c)示意图, (d) AIA 171Å 图, (e) 空时图 [Movie](#)

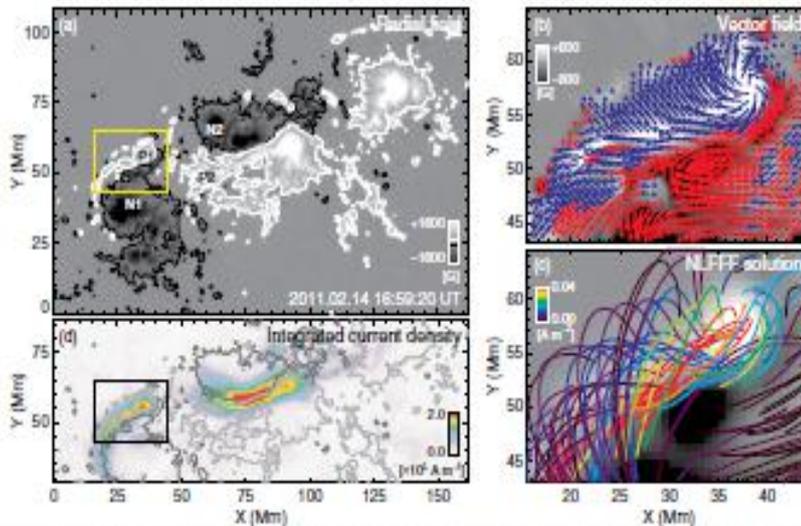


Figure 3. Snapshot of magnetic field of AR 11158, 25 minutes before the eruption. (a) Radial magnetic field (R_r) map as derived from the vector magnetogram. The contours are for ± 200 G. P1, N1, P2, and N2 mark four components of the quadrupolar flux system. The yellow box indicates the FOV for (b) and (c) and is identical to that in (d). (b) Photospheric vector magnetic field map. Gray-scale background shows R_r . The blue/red arrows indicate the horizontal component (H_h) with positive/negative radial component, where field strength $H > 200$ G. Their lengths correspond to the magnitude (H_h); their directions show the azimuth. (c) Selective extrapolated field lines plotted on R_r map. The color shows the amount of radial current at the field line footpoint. (d) Map of current density (J) integrated over the lowest 10 Mm in extrapolated field. The light/dark gray contours are for $R_r = \pm 200$ G. All data are detorted to disk center and remapped using the Lambert equal area projection. (An animation of this figure is available in the online journal.)

图 6. 38: AR 11158 爆发前 25 分钟的磁场, (a)径向磁场, (b)光球矢量磁场, (c)外推磁力线, (d) 电流密度 [Movie](#)

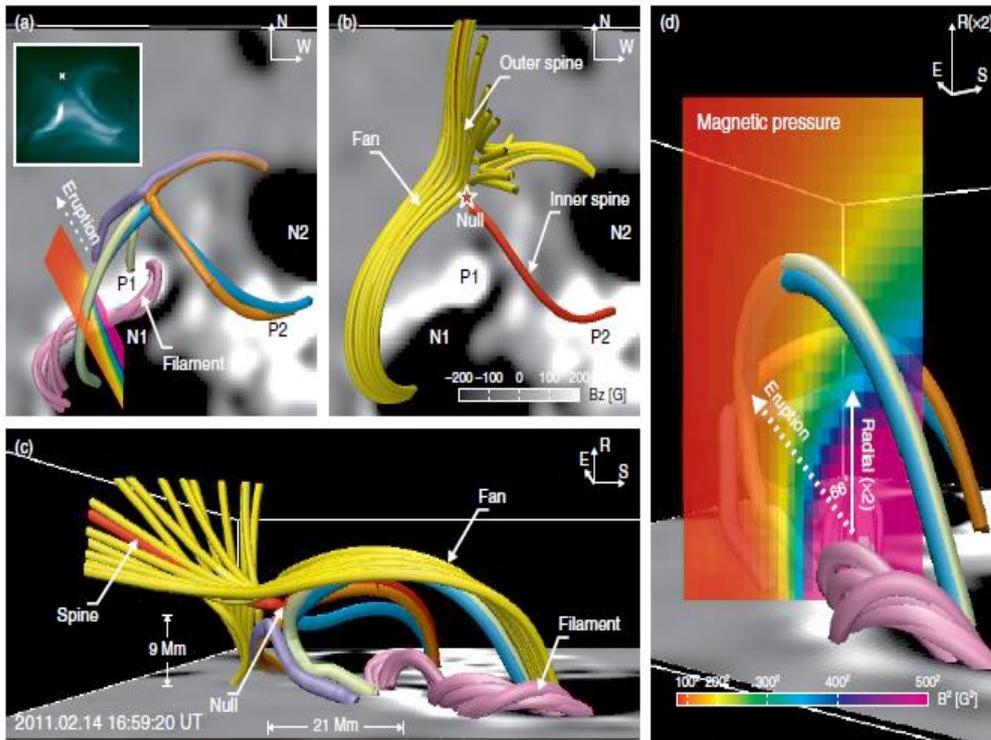


Figure 5. Magnetic topology based on NLFFF extrapolation for the pre-eruption state. (a) *SDO* view of four sets of loops connecting the four quadrupolar flux components pairwise, as well as twisted field lines below representing the AR filament. The cross section (colored plane on the lower left) is identical to that in (d). Inset shows the corresponding AIA 94 Å image, which is the same as Figure 6(a). The inferred coronal null point, marked by “X,” appears slightly above the observed loops. (b) Magnetic null point, spine field line, and open field lines that outline the separatrix (fan) surface. (c) Side view of the region (from east). (d) Side view with z -axis (radial direction) stretched by 2. Magnetic pressure is imaged on a vertical cross section to illustrate its anisotropy. The cross section is roughly aligned with the direction of eruption, and is in front of the null from this viewing angle.

(An animation of this figure is available in the online journal.)

图 6. 39: NOAA11158 活动区 NLFFF 外推磁场拓扑 [Movie](#)

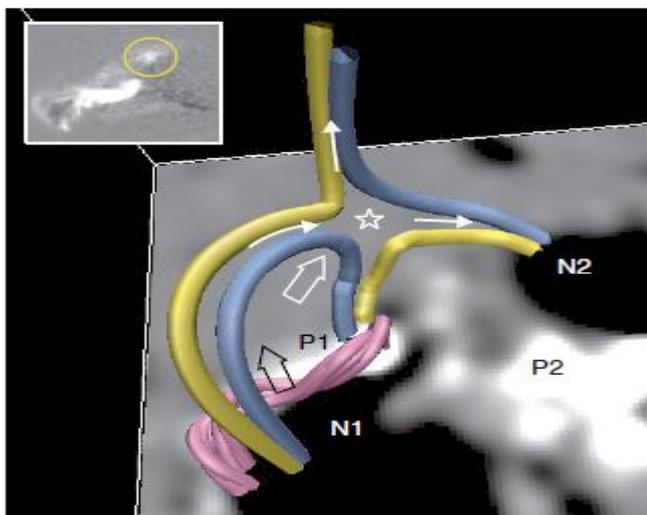


Figure 7. Schematic illustration of the magnetic configuration and dynamics that may have led to the eruption. The structure resembles that of a blowout jet. The arcade (blue field lines above P1/N1) from the newly emerged bipole expands, reconnects with the pre-existing field (blue field lines from N2), becomes open (yellow field lines from N1), and the low-lying sheared/twisted core field (pink field lines between P1/N1) subsequently erupts. A possible initial reconnection site nearby is marked by the star; possible motions of the loops are denoted by thick arrows. Pre- and post-reconnection field lines are colored blue and yellow, respectively. The directions of the observed, *post-eruption* flow (Figure 2 and animation; see also Thompson et al. 2011; Su et al. 2012) are denoted by thin arrows. The inset shows the SXR difference image between 17:22:32 and 17:19:56 UT from *Hinode* XRT Ti Poly filter (FOV $72'' \times 60''$). The brightening P1/N2 loop is marked by a yellow circle; the brightening filament is visible in the foreground.

图 6. 40: 解释示意图

6.2.12.2011 年 2 月 15 日 NOAA 11158 活动区 X2.2 白光耀斑的速度与磁场瞬变

Maurya 等 (2012, APJ, 747, 134) 分析了 2011 年 2 月 15 日 SDO/HMI 观测的 NOAA 11158 活动区, 耀斑峰值期间, 探测到磁场与多普勒速度 (DV) 瞬变现象出现在主黑子本影边界处。这些瞬变现象持续了几分钟, 在空间与时间上与耀斑核对应, 瞬变处的磁场极性翻转, 同时 DV 增加, 这些变化在斯托克斯所有参量中都有反应。

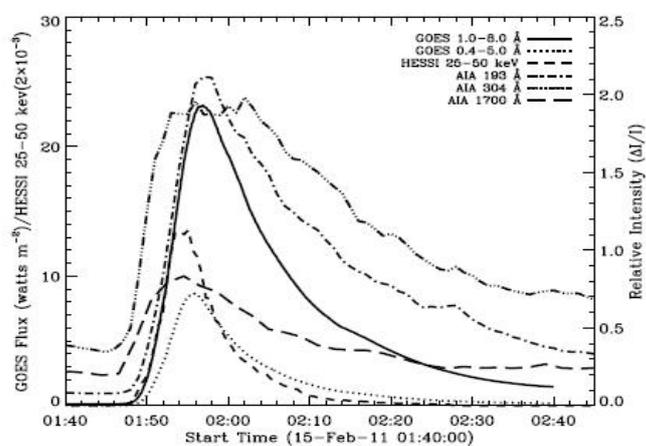


Figure 3. Intensity profiles of the X2.2 flare on 2011 February 15 in different wavelengths.

图 6.41: 不同波段 X2.2 耀斑的强度

6.2.13.MHD 模拟 2011 年 2 月 15 日 X2.2 耀斑：与观测比较

Inoue 等 (2014, APJ, 788, 182) 用 SDO/HMI 数据对 NOAA11158 活动区的 X2.2 耀斑进行了非线性无力场 (NLFFF) MHD 外推以便理解耀斑的动力学, 发现 NLFFF 从来没有显示观测看到的引人注目的动力学行为, 即它是稳定状态而不是扰动。另一方面, MHD 模拟显示, 当在中性线附近形成强剪切线 (通过 tether-cutting 重联产生) 时, 它们最终会通过复杂重联从太阳表面爆发掉。这种结果支持如下论点, 在 NLFFF 通过 tether-cutting 重联形成的强剪切线负责打破磁场在底日冕力的平衡条件。在起始阶段, 由缠绕线形成的重联引起的足点的空间形状与观测到的两带耀斑一致。有趣的是, 在耀斑之后, 重建的场线转变成的结构与耀斑后环很像, 正如 SDO/AIA EUV 图像观测到的, 最终, 它们发现缠绕线超过了一临界高度, 此处通量管变成对环面不稳定。

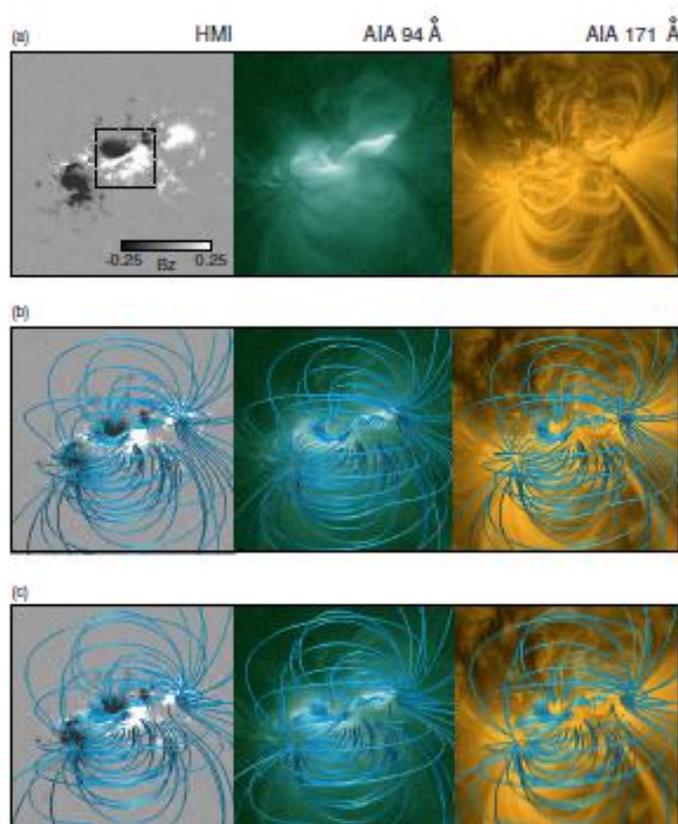


Figure 1. (a) Photospheric vector field (left), and EUV image with 94 Å (middle), with 171 Å (right) observed at 00:00 UT on 2011 February 15, taken by HMI and AIA on board SDO, are shown, respectively. These sizes are in the range of $216 \times 216 \text{ Mm}^2$ and observed tangential components inside the black dashed square ($79.2 \leq x \leq 136$, $8.86.4 \leq y \leq 146$) (Mm), while other axes are fixed by the potential field. The value of B_z is normalized by 2500 G; the one-dimensional value 0.25 corresponds to 625 G. (b) Field lines of the NLFFF are plotted over each image. (c) Field lines of the NLFFF that is reconstructed using the whole vector field, not partial source structure such as in panel (b), are plotted over each image. (A color version of this figure is available in the online journal.)

图 6.42: 2011 年 2 月 15 日 0000UT HMI 光球矢量场 (左), EUV 94 Å (中)、171 Å (右)

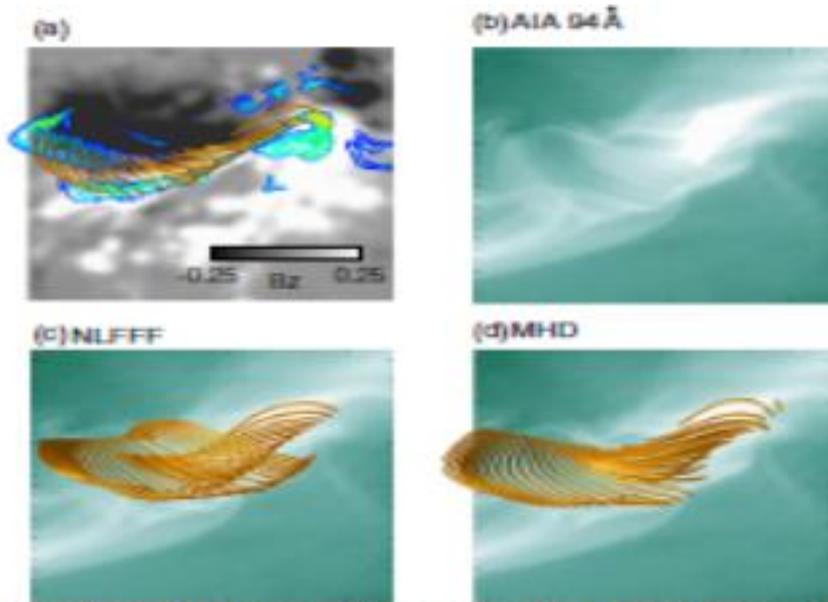


Figure 8. (a) Field lines are plotted with the map on spatial variance of the footpoint caused by the reconnection at $t = 5.0$, which is the same format as in Figure 7(b), over the B_z distribution in gray. (b) AIA image in 94 Å taken by SDO observed at 02:29:50 UT on February 15. (c) Field lines of the NLFFF, which are reconstructed from the vector field observed at 03:00 UT on February 15, are plotted over the AIA image in panel (b). (d) Field lines from MHD simulation at $t = 10$ are plotted over the AIA image.
(A color version of this figure is available in the online journal.)

图 6. 43: 场线 (a)、AIA 94 Å 图(b)、NLFFF 场线(c)、MHD 场线(d)

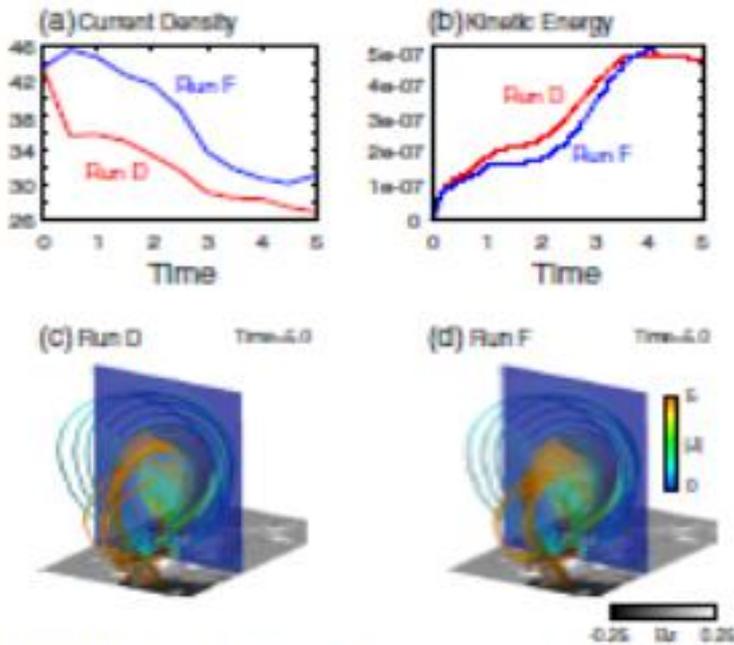


Figure 11. Temporal evolution of the (a) maximum current density (J_{\max}) measured above 3600 km, which corresponds to five grids above the photosphere, and (b) kinetic energy for Run D and Run F in red and blue, respectively. The 3D field line structures with 2D $|J|$ map at $t = 5.0$ are plotted in (c) Run D and (d) Run F. Field line format is the same as in Figure 5.
(A color version of this figure is available in the online journal.)

图 6. 44: 电流密度与动能的演化

6.2.14. 触发 NOAA11158 活动区 M6.6 耀斑的磁场系统

Toriumi 等 (2013, APJ, 773, 128) 利用 SDO/HMI 及 SDO/AIA 数据分析了 2011 年 2 月 13 日 NOAA 活动区的 M6.6 耀斑, 该耀斑由两个大浮现偶极子构成, 发现在这个四极活动区中心, 通过的磁元的自行运动形成高剪切的极性翻转线 (PIL), 在 PIL 上方形成剪切的冕拱。观测支持这样的解释, 目标耀斑由具有入侵结构 (正极性穿入负极性) 的磁场局部区域触发。发现触发区域的形成是由小规模磁场快积累导致。他们的分析结构显示, 在触发耀斑活动的过程中, 包括各种规模的所有磁系统, 不仅包括整个活动区演化, 还包括磁场精细结构。

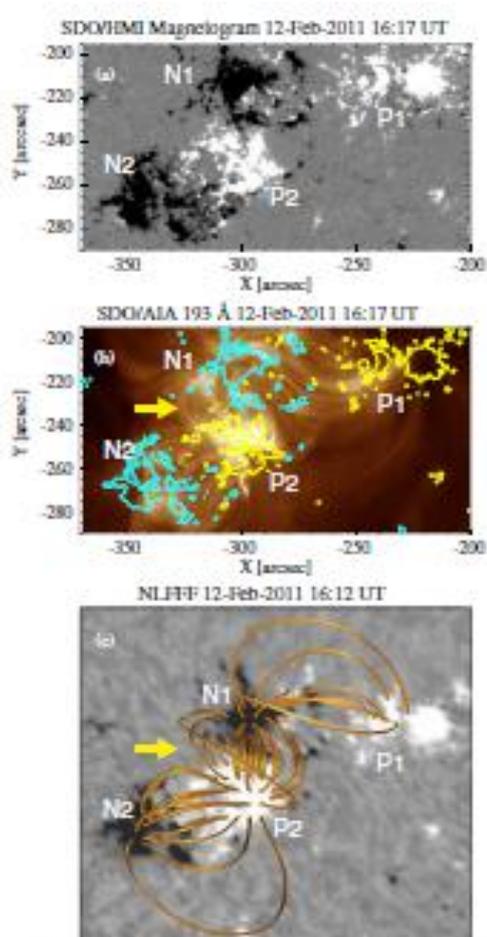


Figure 3. (a) SDO/HMI magnetogram of NOAA AR 11158 taken at 16:17 UT on 2011 February 12, ~ 1 day before the M6.6 class flare. The gray scale saturates at ± 200 G and the axes are in arcseconds from the disk center. Numbers representing two bipolar pairs (P1-N1 and P2-N2) are overplotted. (b) SDO/AIA 193 Å image taken at the same time as in panel (a). Contour levels of ± 200 G are indicated by yellow and cyan lines. (c) NLFFF calculated from the HMI magnetogram. Arrows in panels (b) and (c) show the coronal arcade connecting N1 and P2.

(A color version of this figure is available in the online journal.)

图 6.45: (a)2011 年 2 月 12 日 16:17 UT NOAAAR 11158 SDO/HMI 磁图, (b) SDO/AIA 193Å 图, (c) NLFFF 模型结果

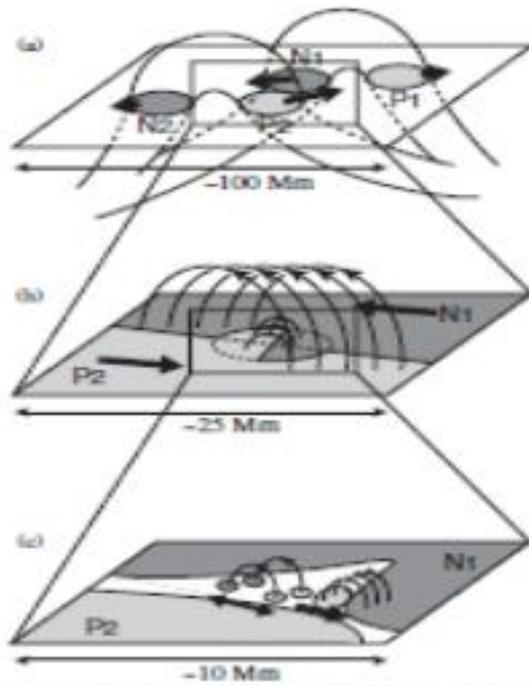


Figure 3. Schematic illustration of the magnetic structure in multiple scales that are involved in the M6.6 class flare in NOAA AR 11158. (a) Ellipses on the plane (photosphere) indicate the two major bipoles, P1-N1 and P2-N2. Lighter and darker shadows indicate the positive and negative polarities, respectively. Tubes above and below the photosphere show the expected flux tubes that compose this AR. (b) Closer of the PIL between N1 and P2. Relative motions in both sides of the PIL, along the overlying coronal arcade, while, in the core of the PIL, the flare-triggering region (distorted structure) with the RS-component flux appears. (c) Normal view of the triggering region is illustrated. Small-scale bipoles converge in the gapped PIL, and the positive patch is advected to collide with the N1 polarity, forming an RS flux through magnetic reconnection.

图 6. 46: 各种规模的磁结构参与 NOAA 11158 活动区 M6.6 耀斑示意图

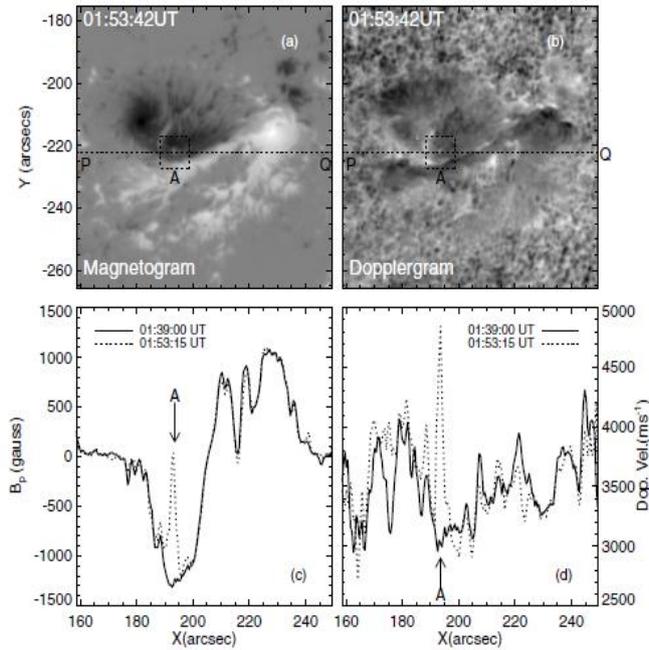


Figure 4. AR NOAA 11158 at the peak phase of the X2.2 flare on 2011 February 15: (a) the magnetogram and (b) the Dopplergram. The box labeled "A" marks the area where TFs were observed. The bottom panels (c) and (d) show the corresponding profiles along the line PQ at the pre- and peak phases of the flare represented by solid and dotted curves, respectively.

图 6. 47: NOAA 11158 活动区 X2.2 耀斑在峰值阶段 (2011, 2, 15) 磁图(a)与多普勒速度(b)

6.2.15. 日冕磁场外推

当前的非线性无力场 (NLFFF) 外推模型主要用于底日冕。江朝伟和冯学尚 (2013, APJ, 769, 144) 用 MHD 松弛法发展了一新 NLFFF 模型来重建日冕磁场, 这种方法基于 CESE - 具有保护元/解决元空时方案的 MHD 模型, 并利用 SDO/HMI 数据应用于 NOAA 11158 和 11283 活动区, 两者非势性都较强, 产生 X 级耀斑与爆发。对原始磁图进行预处理来去除力。该码重建的磁力线与 (SDO/AIA) EUV 观测到冕环很像, 活动区多数重要特征重现的相当好, 如高剪切场线及缠绕通量绳, 无力限制在强场区表现的非常好, 但在弱场表现的不尽完美。

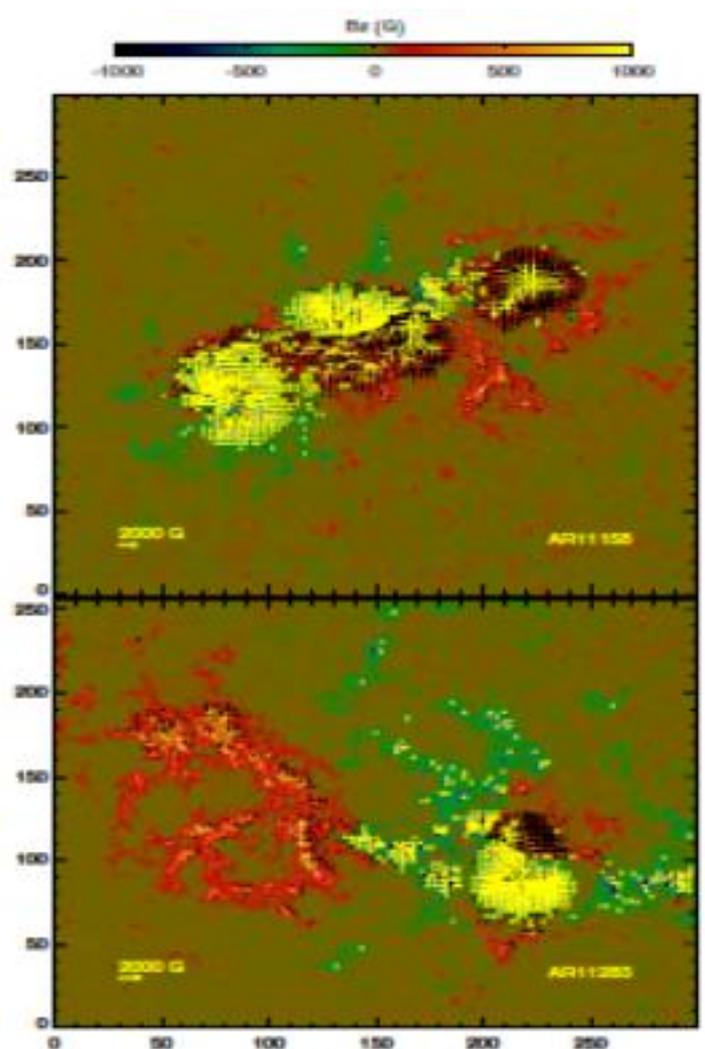


Figure 2. Vector magnetograms for AR 11158 and AR 11283. The background shows the vertical components with saturation values of ± 1000 G; the vectors represent the transverse fields (above 200 G). The length unit is arcsec. (A color version of this figure is available in the online journal.)

图 6.48: 11158 及 11283 活动区矢量磁场

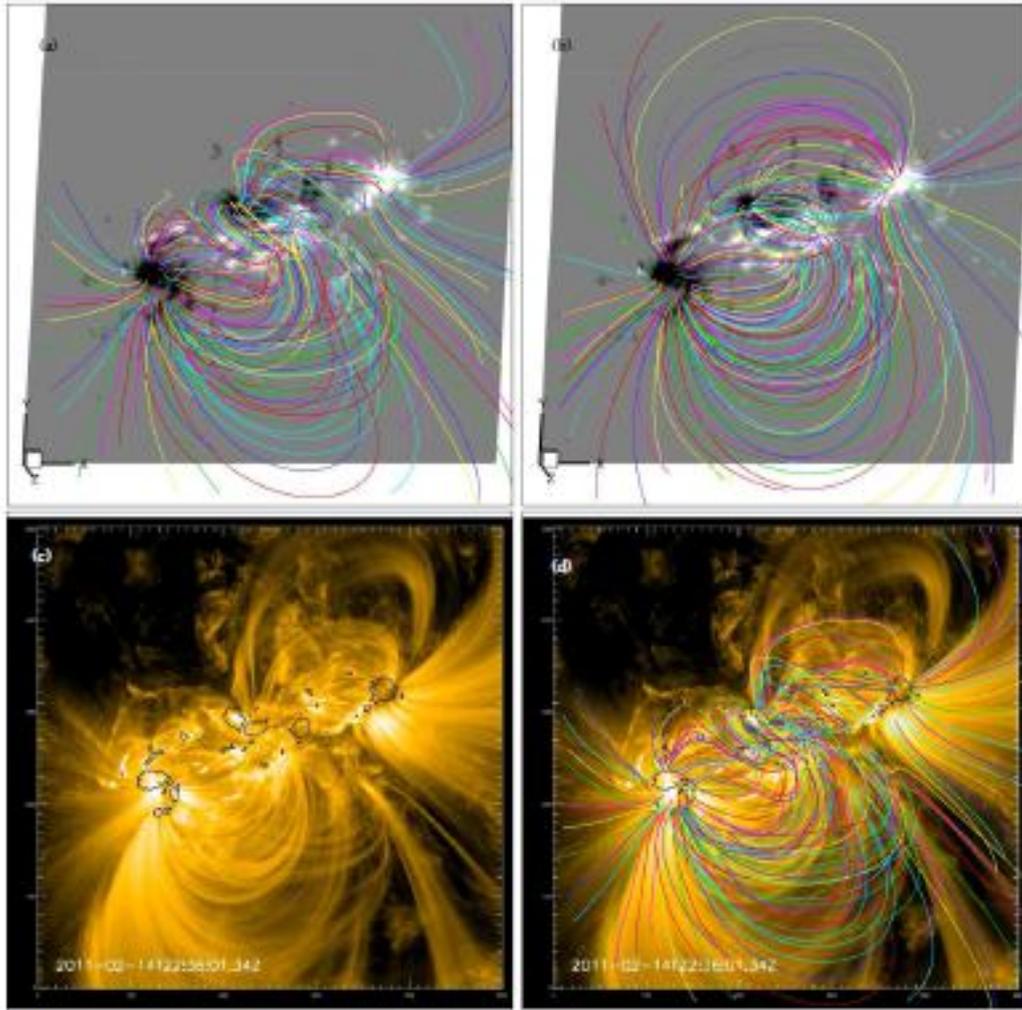


Figure 5. Comparison of extrapolation field lines with AIA 171 Å loops for AR 11158: the NLFFF lines (a), the potential field lines (b), the AIA image (c) and NLFFF lines overlaying the AIA image (d). Contour lines for ± 1000 G (the black curves) of line-of-sight photospheric field are overlaid on the AIA images, and for all the panels the field lines are traced from the same set of footpoints on the bottom surface.
(A color version of this figure is available in the online journal.)

图 6. 49: 11158 活动区外推与 AIA 171Å 环比较, (a) NLFFF 外推, (b) 势场线, (c) AIA 图, (d) NLFFF 与 AIA 叠加

6.2.16. NOAA 11158 耀斑的触发过程研究

Bamba (2013, APJ, 778, 48) 使用 Hinode/SOT 数据, 分析了耀斑前磁场结构和钙 II H 发射线的时间-空间相关性, 发现磁剪切角都超过了 70 度, 在耀斑前相就发生了磁场扰动: 一类是反极性, 另一类是反剪切, 非常小的磁场扰动也可能触发大的耀斑。

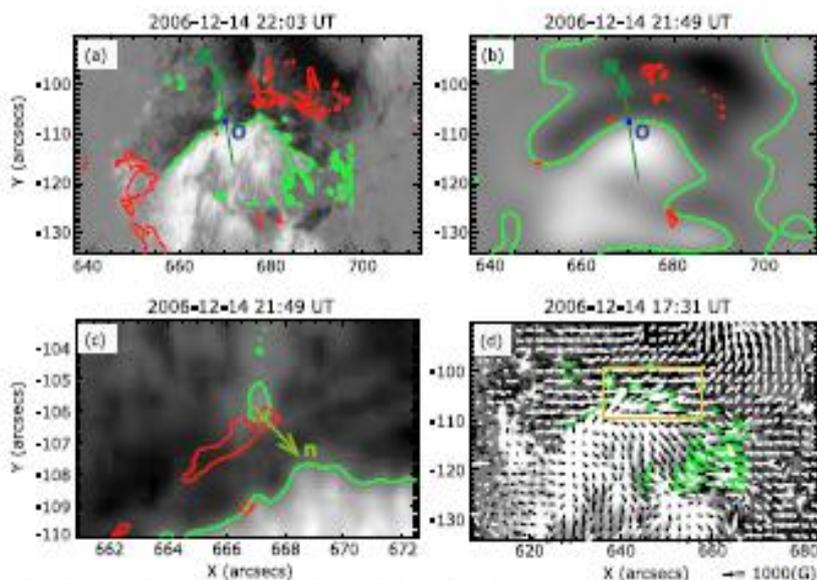


Figure 5. Images from which the azimuth ϕ and the shear angle θ were measured in Event 2. The respective panels are illustrated as for Figure 2. The trigger point O and vectors N and π are defined as shown in panels (a), (b), and (c) of Figure 2. The shear angle θ was measured in the region indicated by the yellow square in panel (d). The intensity scale saturates at ± 0.1 in panels (a)-(c) and at ± 1000 G in panel (d). (A color version of this figure is available in the online journal.)

图 6. 50: NOAA 11158 活动区事件 Stokes-V/I 分布。

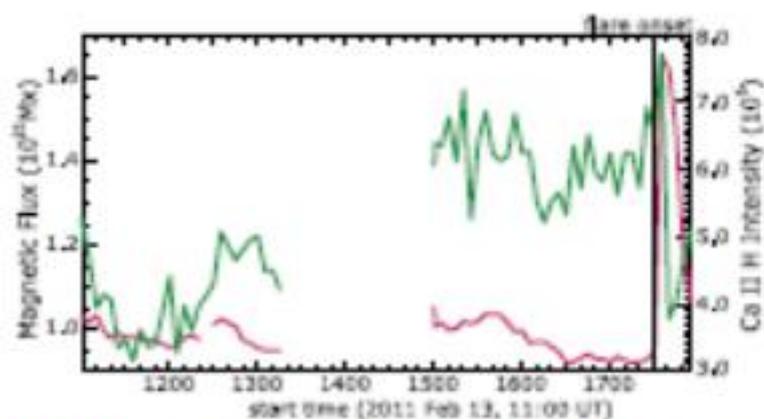


Figure 12. Temporal evolution of positive magnetic flux and Ca II H intensity prior to the M5.6 flare onset on NOAA AR 11158. The vertical solid line marks the onset time of the flare, 16:30 UT 2011 February 13. The image is formatted as described for Figure 30(b). The region of positive magnetic flux and Ca II H intensity is delineated by the yellow squares in Figures 11(a) and (c). (A color version of this figure is available in the online journal.)

图 6. 51: NOAA 11158 活动区事件正磁通与钙 II 线强度演化

6.2.17. 产生 11158 活动区 X 和 M 级耀斑的磁结构

Inoue 等 (2013, APJ, 770, 79) 基于 SDO/HMI 数据, 用他们发展的松弛非线性无力场外推方法研究了 11158 活动区产生的 M6.6、X2.2、M1.0 和 M1.1 耀斑的磁扭曲 (twist), 发现在 M6.6 和 X2.2 耀斑前从半圈到一圈的强扭曲场线, 在耀斑后消失, 保持到耀斑之后的大部分 twist 小于半圈。在 M1.0 和 M1.1 耀斑前也建立了强扭曲, 大部分保持到之后。通过 M1.0 和 M1.1 耀斑前拓扑分析, 强扭曲线大多被弱扭曲线包围, 后者与正黑子的顺时针运动一致, 足点根植于强磁场区。这意味着这些弱扭曲线可能抑制后面两个 M 级耀斑强扭曲线的活动。

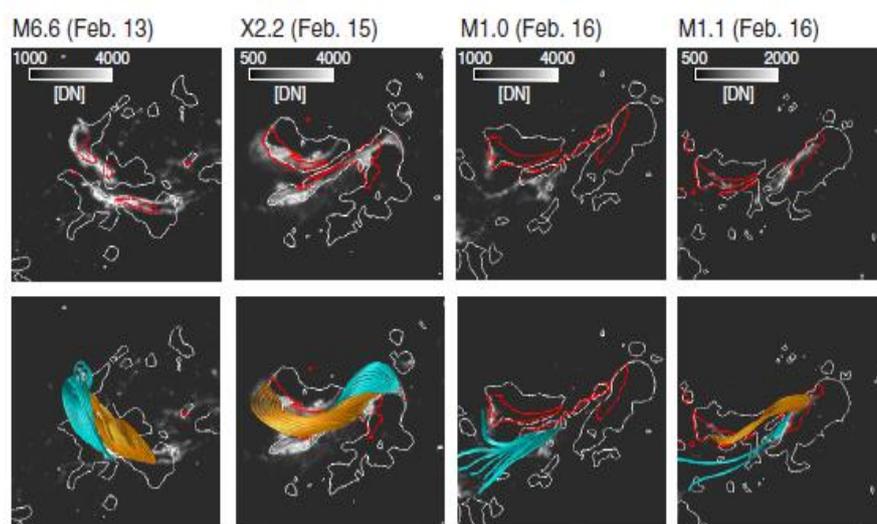


Figure 3. Upper panels show the normal component of the magnetic field and twist profile plotted on the Ca II image before the each flare. The white lines represent the contours of the normal component of magnetic field ($|B_z| = 625$ G) observed at the same times as shown in Figure 1(b). The red lines show the magnetic twist ($T_n = 0.5$) obtained from the NLFFF extrapolated from each vector field. The regions surrounded by red lines are occupied by strongly twisted lines ($T_n > 0.5$). The gray scale shows Ca II image observed at 17:35:38 UT on February 13, 01:50:18 UT on February 15, 01:40:39 UT and 07:42:13 UT on February 16, respectively. The lower panels show the selected magnetic field lines traced from the regions in which Ca II illuminates strongly. The orange and blue field lines represent twist values more and less than half-turn twists ($T_n = 0.5$), respectively.

(A color version of this figure is available in the online journal.)

图 6. 52: 法向磁场与 twist 轮廓 (上), 磁力线 (下)

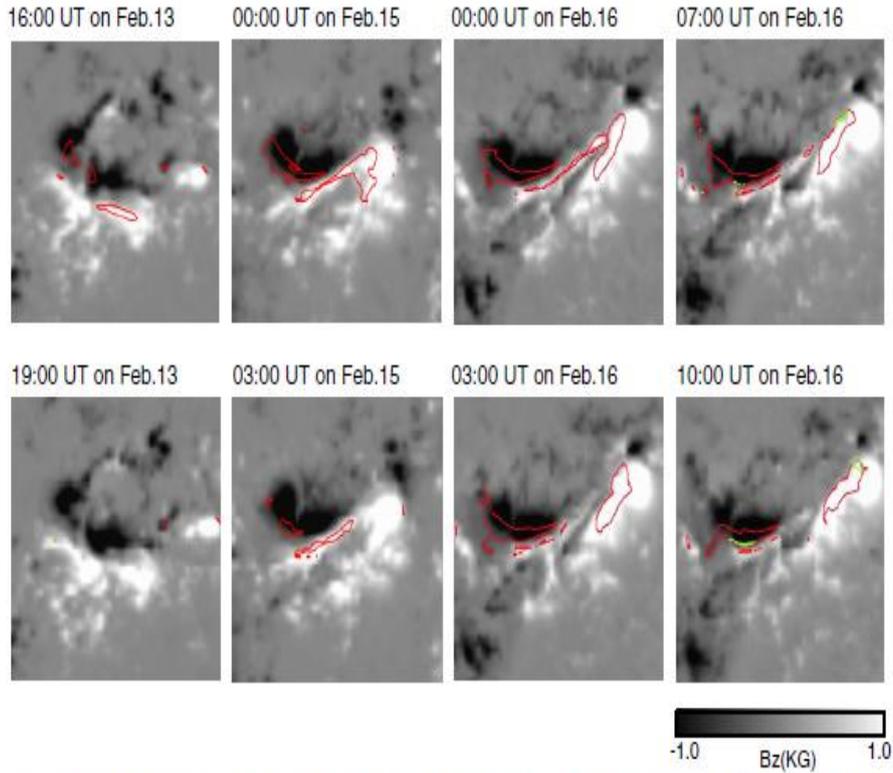


Figure 4. Temporal evolution of the magnetic twist with the distribution of B_z component in gray scale, which corresponds to the central area of the active region. The upper and lower panels represent 40-90 minutes before and after each flare (M6.6, X2.2, M1.0, and M1.1), respectively. The red and green lines represent the contours of the magnetic twist $T_n = 0.5$ and $T_n = 1.0$, respectively. The regions surrounded by red and green lines indicate strongly twisted regions of $T_n > 0.5$, and $T_n > 1.0$, respectively.

图 6. 53: 磁扭曲与 B_z 演化

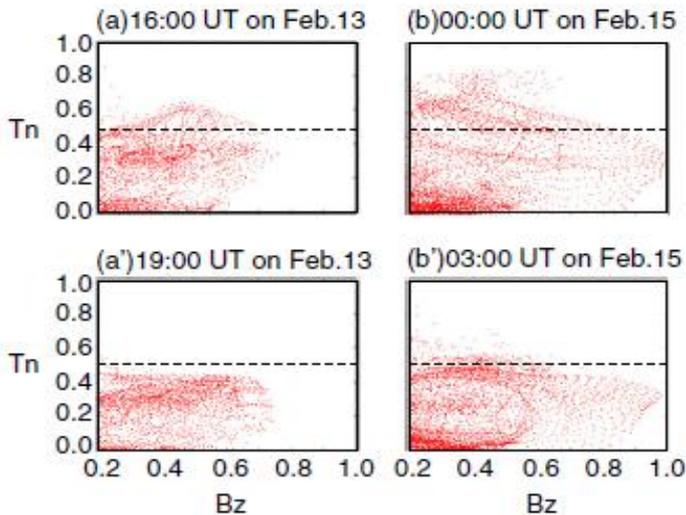


Figure 6. (a) and (b) Distribution map related to the twist (vertical axis) and the B_z components (horizontal axis) at 16:00 UT on February 13 and 00:00 UT on February 15 (before M6.6 and X2.2 flares, respectively). The B_z component is focused on values in excess of 500 G, whose normalized value corresponds to 0.2. The horizontal dashed line indicates the value of a half-turn twist ($T_n = 0.5$). (a') and (b') Maps in same format at 19:00 UT on February 13 and 03:00 UT on February 15 corresponding to the period after the M6.6 and X2.2 flares, respectively.

图 6. 54: M6.6 和 X2.2 耀斑前 twist - B_z 关系图

6.2.18.2011 年 2 月 15 日震动耀斑的磁声能研究

Alvarado-Gómez 等 (2012, Solar Physics, 280, 335-345) 基于 DSO/HMI 多普勒图数据用局部日震学方法识别 11158 活动区的震动源, 用 RHESSI 硬 X 射线数据来检测耀斑期间震动源的位置与粒子沉降点的关系。根据 HMI 数据, 光球视向磁场中波动的时间轮廓用来估计观测到震动信号的区域中磁场的变化, 这样可以估计洛伦兹力对光球源区的做功, 这占了震动辐射大部分声能, 因此, 洛伦兹力对太阳震动贡献相当大。可是, 也有这样的区域, 洛伦兹力很强, 但并没有明显的声辐射。

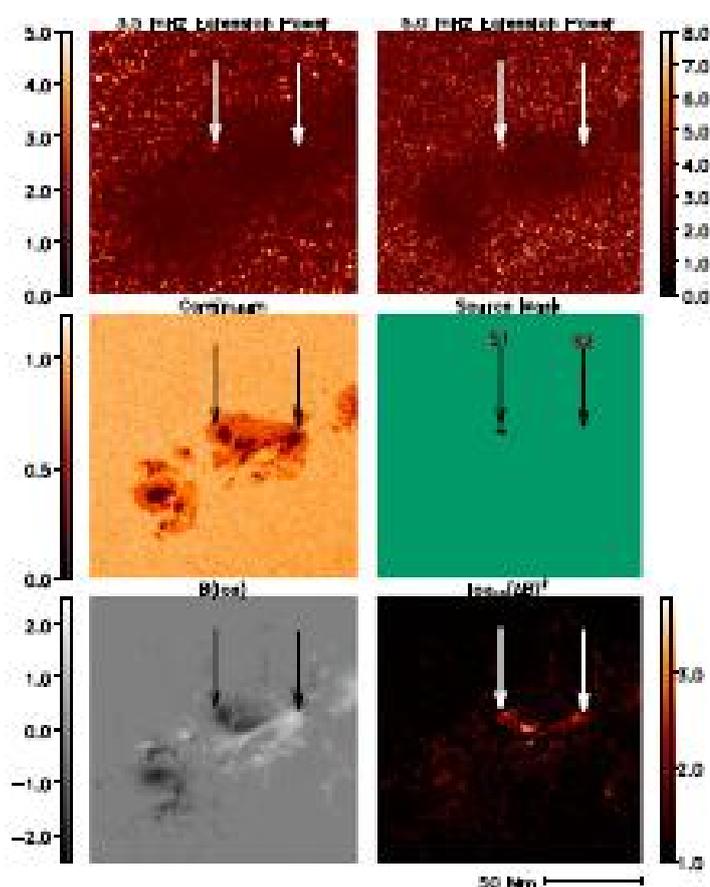


Figure 2. Acoustic source distribution for the flare of 15 February 2011 in NOAA AR11158. Upper panels show the 2.5–4.5-mHz and 5.5–6.5-mHz spectrograms normalized to unity in the mean quiet Sun. Center-left frame shows the continuum image of the flaring region while the middle-right frame shows a threshold mask whose value is unity (dark) in the source region and null (green) elsewhere. Lower left shows the pre-flare line-of-sight magnetic field in kG. Lower right shows the base-ten logarithm of the mean-square line-of-sight magnetic variation in the 2.5–4.5-mHz spectrum during the impulsive phase of the flare. Arrows labeled “S1” and “S2” show the locations of compact acoustic sources whose energy spectra are labeled “Source 1” and “Source 2,” respectively, in Figure 1. The lack of a significant signature at the location labeled “S2” in the upper-left frame signifies that acoustic emission from Source 2, while significant in the 5.5–6.5-mHz band, is insignificant in the 2.5–4.5-mHz band.

图 6. 55: NOAA 11158 活动区的声源分布

6.2.19.NOAA 11158 活动区磁拓扑的时间演化

Zhao 等 (2014, APJ, 787, 88) 基于 DSO/HMI 数据, 利用日冕三维磁场重建, 分析了 NOAA 11158 活动区磁拓扑的时间演化, 通过计算挤压程度因子 Q , 得出的准分割层(QSL) 显示这个活动区有一个由磁四极子形成的全局拓扑, 包括一个相当稳定的双曲通量管 (HFT) 结构。强 QSL 与高剪切拱对应, 与通量绳的形成有关。在 M6.6 和 X2.2 耀斑刚开始前 QSL 非常突出, 这意味着强 QSL 与 11158 活动区的高耀斑产率存在密切的关系。此外, 在 X2.2 耀斑前 QSL 上方发现一个小的反泪珠 HFT 结构, 说明这个地方存在磁通量绳。即便如此, 还存在了一个全局构型 (HFT), 证明在爆发期间大规模 HFT 仅起次要作用。总之, 他们排除了基于爆发 (breakout) 模型的触发, 而强调通量绳的中心作用。

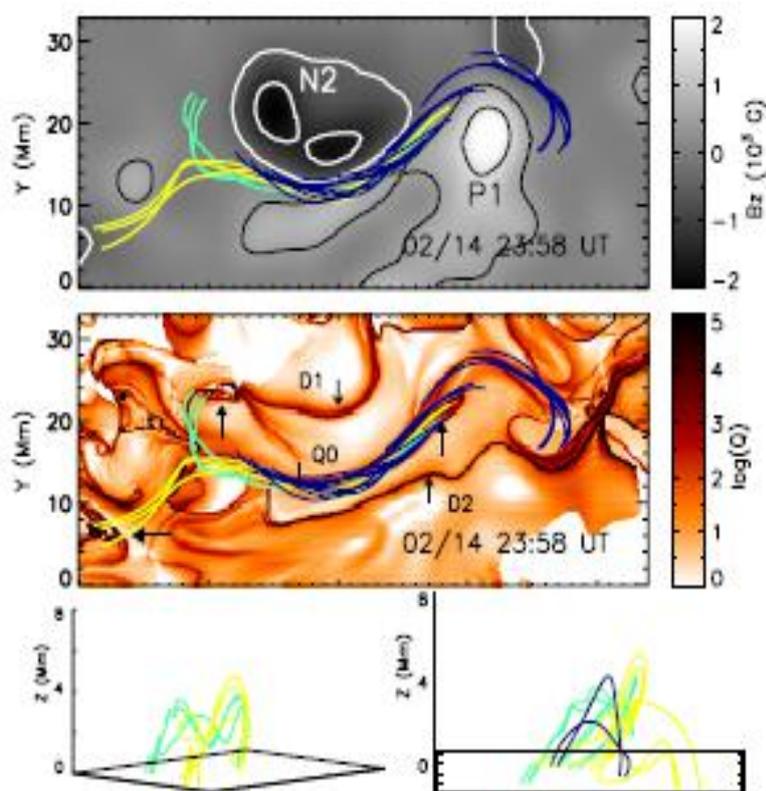


Figure 7. Top: B_z map with overplotted magnetic field lines at 23:58 UT on February 14. The FOV is delineated by the dashed rectangular box in Figure 1. Middle: Q map with overplotted magnetic field lines. Bottom: two perspective views of the field lines plotted in upper panels, with the same FOV in the X - Y plane. (A color version of this figure is available in the online journal.)

图 6. 56: B_z (上)、 Q 值与磁力线叠加 (中)、两个透视图 (下)

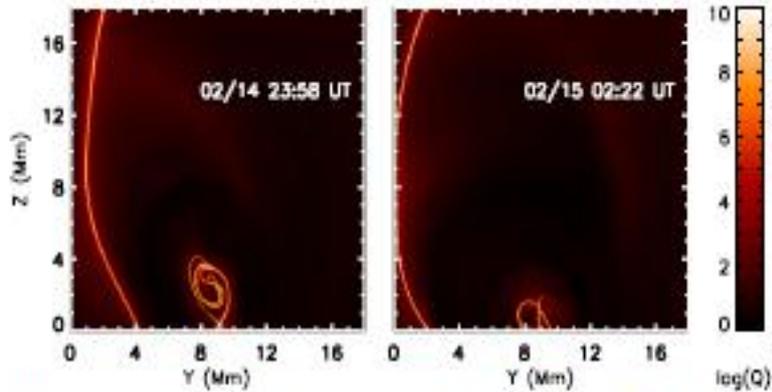


Figure 9. Q maps before and after the X2.2 class flare for the vertical cuts shown in Figure 8 by the white lines. (A color version of this figure is available in the online journal.)

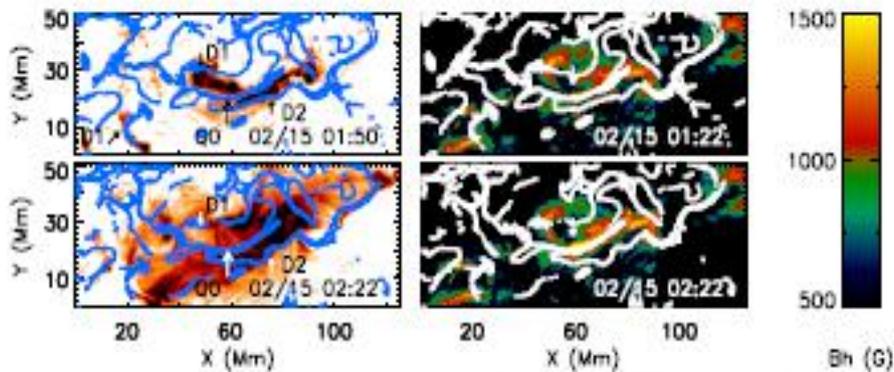


Figure 10. Left: AIA 304 Å images at 01:50 UT (upper panel) and 02:22 UT on February 15 (lower panel), superimposed with Q values (contour). Right: Q values are superimposed on the horizontal magnetic field at 01:22 UT (upper panel) and 02:22 UT on February 15 (lower panel). The blue and white contours in the panels indicate the main QSLs in this region. The Q maps in the upper/lower panels are at 01:22 UT/02:22 UT in the lower panels on February 15, respectively.

图 6. 57: AIA 304Å图与 Q 值叠加 (左)、Q 值与水平磁场叠加 (右)

6.2.20.2011 年 2 月 15 日 X2.2 耀斑的突然光球运动与黑子旋转

Wang 等 (2014, APJL, 782, L31) 基于 SDO/HMI 数据, 利用微分放射速度估计方法和傅里叶局部相关跟踪方法, 计算了 NOAA 11158 活动区光球流动的速度和涡度, 并分析了其时间演化。结果显示, 磁极性翻转线周围的剪切流突然降低, 在耀斑脉冲相期间旋转运动突然变化。这些结果可由 Hudson 等和 Fisher 等提出的洛伦兹变解释, 这种机制可以解释快速而不可逆的光球矢量磁场变化和观测到的与耀斑有关的短期运动之间的联系。特别是由洛伦兹力提供的转矩变化与观测到的角速度所需要的一致。

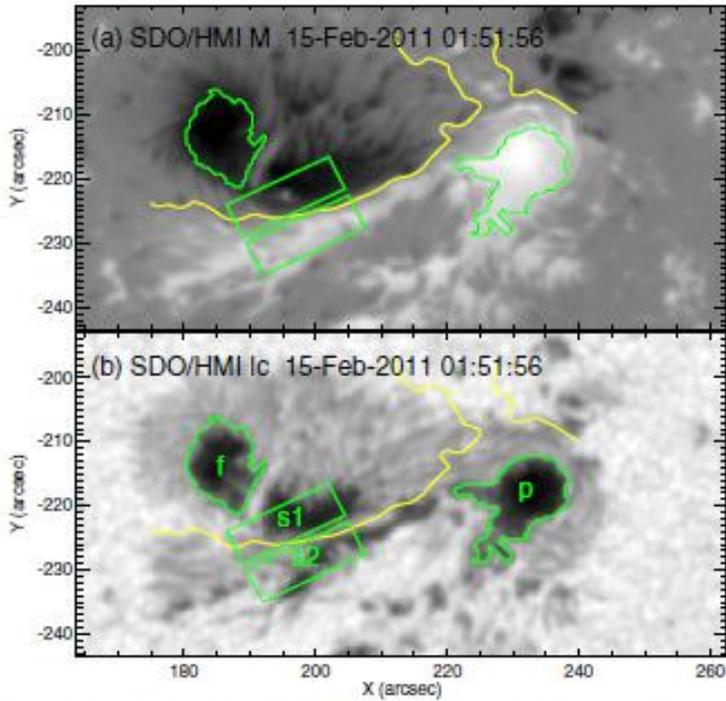


Figure 1. Maps of AR 11158 with regions of interest marked by green contours. (a) *SDO/HMI* line-of-sight magnetogram. (b) *SDO/HMI* intensity image. The yellow curve represents the main flaring PIL.

图 6. 58: 11158 活动区图，关心的区域由绿色表示，(a) SDO/HMI 视向磁图，(b) SDO/HMI 强度图

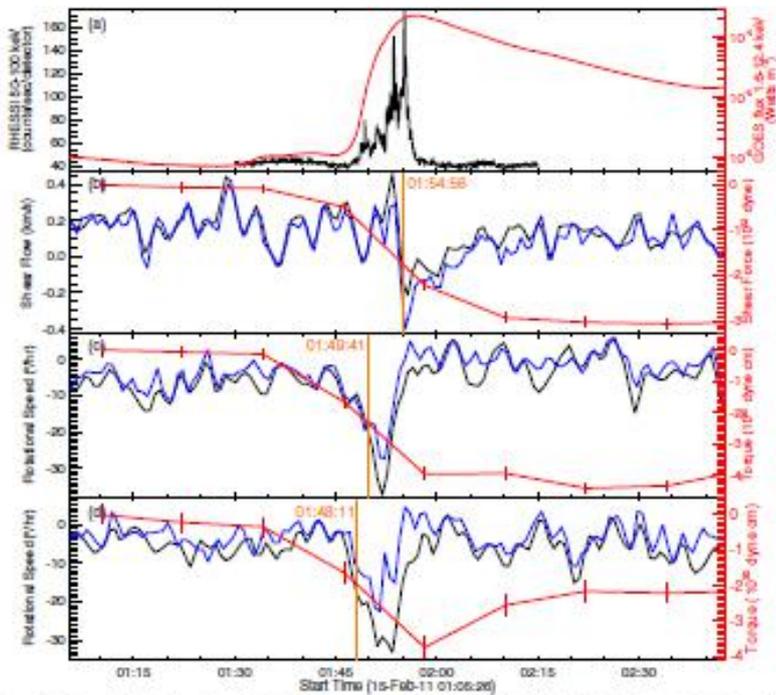


Figure 4. Temporal evolution of the sudden motions. (a) The black curve represents the RHESSI 50–100 keV IXXR light curve. The red curve shows the GOMS 1.5–12.4 keV flux. (b) Time profile of the shear flow near PIL. The black and blue curves represent the mean velocity of the shear flow derived by DAVE and PLCT, respectively. The red curve shows the change of horizontal Lorentz force. (c) and (d) display the time profiles of the regions p and i, respectively. The black curves give the vorticity derived using DAVE flows, while the blue curves are from the PLCT result. The red curves show the torque provided by the change of horizontal Lorentz force. The orange vertical lines marked with time show the starting time of the sudden shear motion and rotation. The error bars of red curves indicate the 3 σ level.

图 6. 59: 突然运动的时间演化

6.2.21. 两个活动区在光球及光球下的水平流动

刘阳等 (2013, *Solar Phys*, 287, 279 - 291) 利用 SDO/HMI 数据, 比较了两个活动区 (AR11084 和 AR11158) 在光球及光球下 (0.5 Mm) 水平流动场。AR11084 是一成熟、简单活动区, 没有显著的耀斑活动, 而 AR11158 是一多极、复杂的活动区, 由磁通浮现。光球流动由微分放射速度估计方法得到, 光球下流动由时间-距离日震学得到。AR11084 活动区在两层发现有相似的结构: 黑子本影内的向内流动及包围黑子的向外流动。内流与外流的边界 (两层稍有差别) 在黑子半影内, 在光球下内流的面积比光球内流面积稍大。对于 AR11158 活动区来说, 在有些区域这两层的流动非常相似, 而在另外区域差异巨大, 在包围黑子的区域, 两层都显示一致的外流。此外, 在光球看到的与通量浮现相关的多数流动特征在光球下并没有响应的对应物, 这意味着由通量浮现引起的水平流动并没有延伸到光球下。

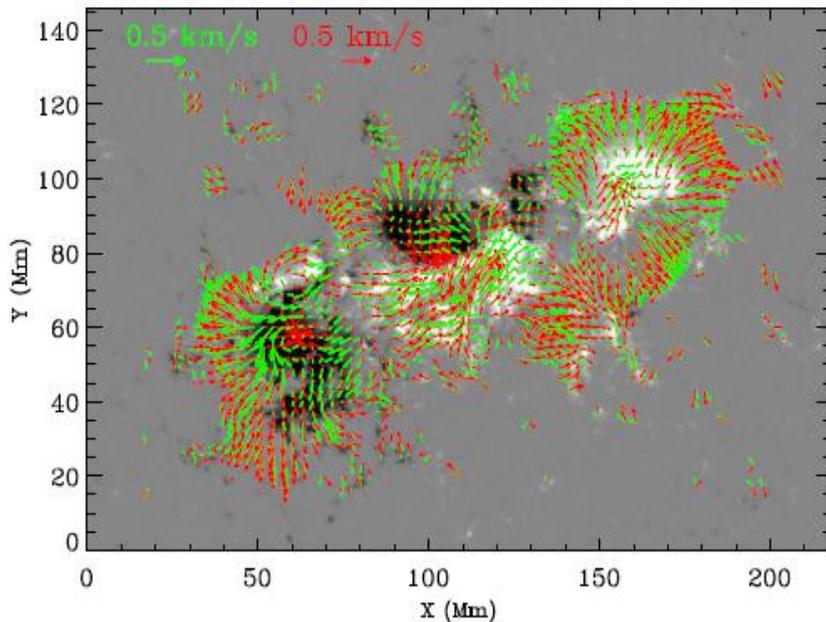


Figure 8 Vertical magnetic field in AR 11158 (image) overplotted by the horizontal velocities in the photosphere (green arrows) and in the -0.5 Mm layer (red arrows). Black and white in the image refer to negative and positive fields, respectively. The photospheric velocity is the same as in Figure 7. The flow in the -0.5 Mm layer is derived by a time-distance helioseismology method applied to eight-hour Dopplergrams observed from 06:00 UT - 14:00 UT 14 February 2011. Only velocities at locations where the horizontal velocity in the photosphere is greater than 0.07 km s^{-1} are plotted.

图 6. 60: 11158 活动区的垂直磁场和在光球 (绿箭头) 及 0.5Mm 之下 (红箭头) 的水平速度

6.2.22.NOAA 11158 活动区的耀斑与磁非势性

宋桥等 (2013, Research in Astron. Astrophys. 13, 226 - 238)利用 SDO/HMI 数据分析了 NOAA 11158 活动区五个非势参量: 电流、电流螺度、源场、光球自由能和角剪切。证实与磁通相比, 磁非势性与耀斑关系紧密, 浮现通量区对理解磁非势性与耀斑非常重要。(1)源场中的涡旋直接显示水平磁场的偏转, 旋转对应延迟的快速旋转黑子, 黑子旋转导致非势增加; (2) 矢量磁场方位角具有明显变化的两个区域是在磁极性翻转线附近; (3) 4 个耀斑期间螺度快速变化且明显增强。

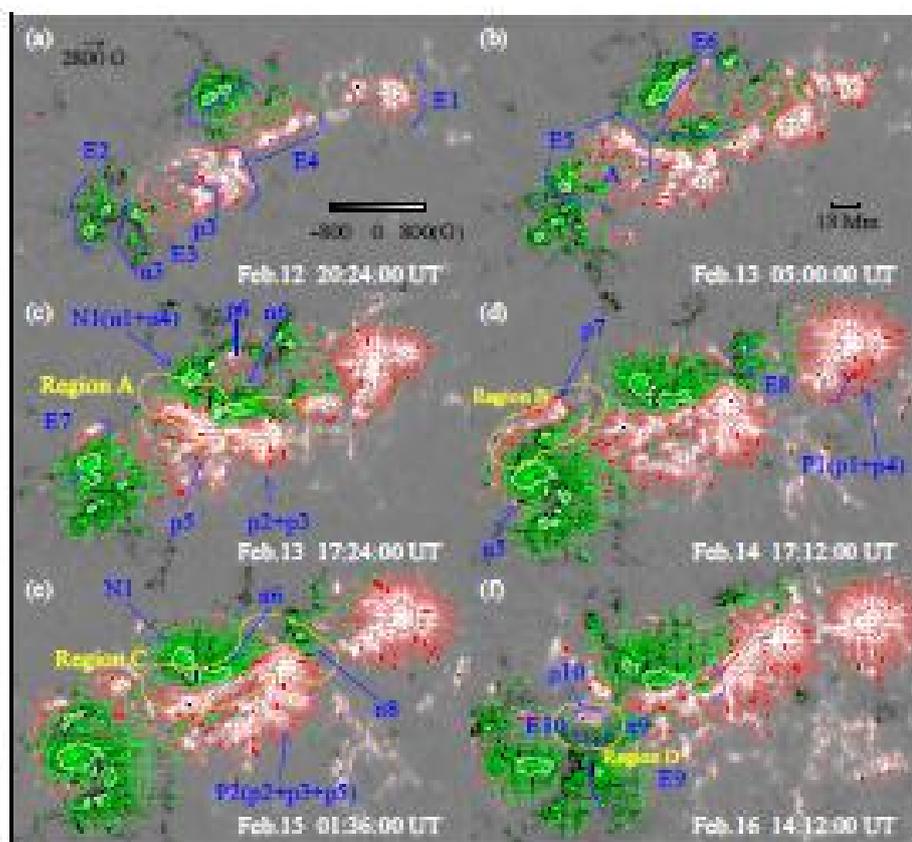


Fig. 1 Overview of vector magnetograms in NOAA AR 11158 from 2011 February 12 to 16. The vertical magnetic component is presented by black-and-white patches and isogone contours with levels 1500 G (black) and -1500 G (white). Green and red arrows denote the horizontal magnetic component. The field of view (FOV) in each panel is about $205'' \times 125''$. E1-E6 in (a) and (b) indicate six major EFRs and E7-E10 in (c), (d) and (f) show four other smaller ones. Letters 'p' and 'a' with numbers indicate the positive and negative polarities that come from corresponding EFRs, respectively. (c)-(f) show the vector magnetic fields just before the onset times of the four major flares (M6.6, M2.2, X2.2 and M1.6), respectively. The yellow contours in the four panels outline regions A, B, C and D (see Sect. 4).

图 6. 61: NOAA 11158 活动区矢量磁图

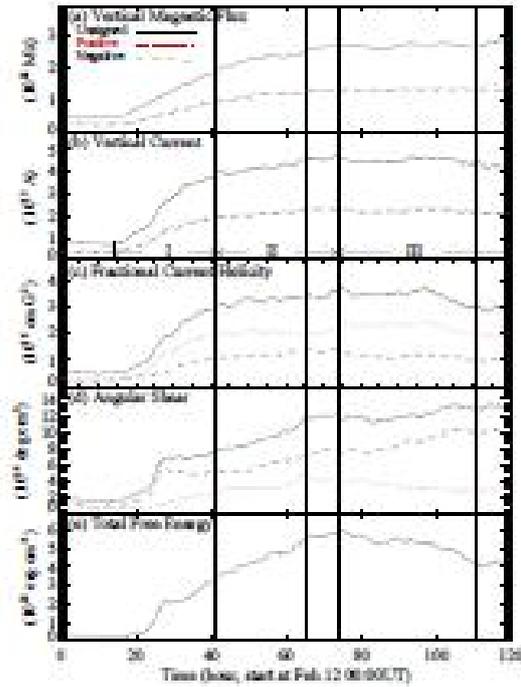


Fig. 3 Evolution of magnetic flux and four non-potential parameters of AR 11158 in five days. (a) is the variation of total unsigned, positive and negative magnetic flux. The four long vertical lines in each panel indicate the onset times of the four flares. (b)–(d) have the same line styles as (a) but for the variations of vertical currents, current helicities and angular shears. (e) is the variation of total free energy. (b) also gives the three phases of the evolution (see Table 2).

图 6. 62: NOAA 11158 活动区磁通及四个非势参数的演化

6.2.23. 与耀斑相关的 III 型射电暴击 EUV 喷流的动力学行为

Chen 等 (2013, APJ, 769, 96) 仔细描述了 11158 活动区 III 型射电暴与耀斑等高能现象之间的关系, Wind/WAVE 及地面射电望远镜阵观测到的 III 型射电暴与 SDO/AIA 及 RHESSI 观测的 EUV 喷流 (jet) 及硬 X 射线辐射在时间上吻合, 显然 EUV jet 与硬 X 射线辐射有共同的源区, III 型射电暴与 jet 足点热的 (7MK) 等离子体有关。

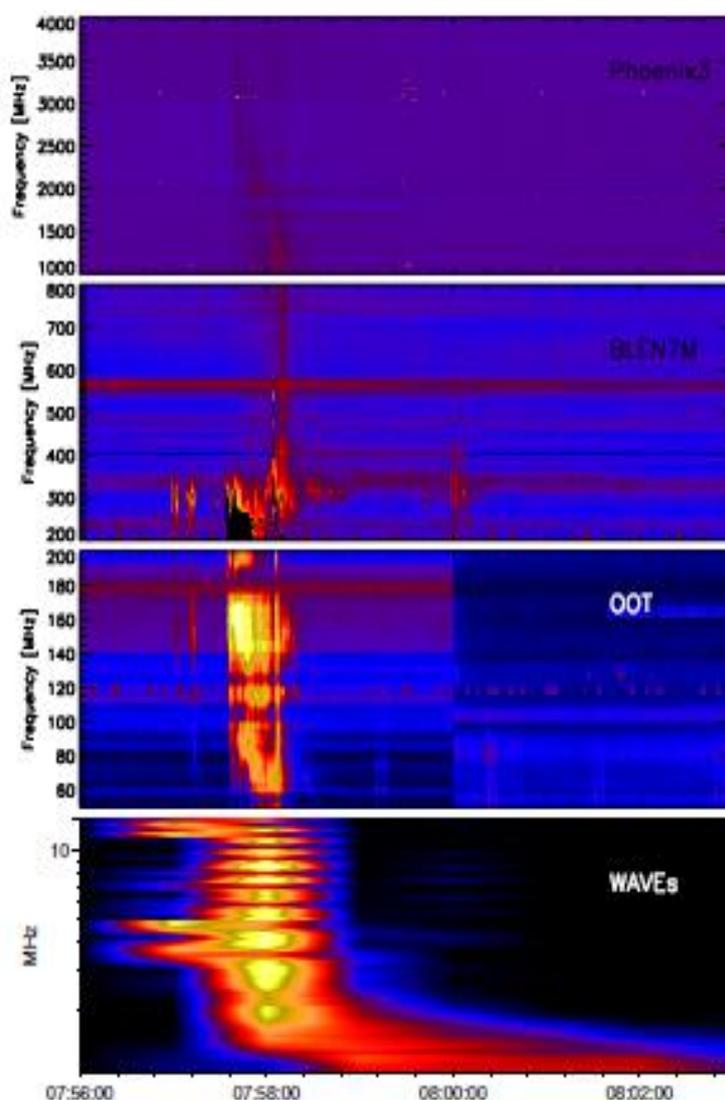


Figure 1. Comparison of the Type III radio burst at different frequency ranges associated with AR11158 at UT 07:58 on 2011 February 15. From top to bottom: Phoenix 3, Helix, Ooty, Wind/Waves.

图 6. 63: 11158 活动区在不同频率范围的 III 型射电暴

6.2.24. 活动区的磁螺度及能量谱

张洪起等 (2014, APJL, 784, L45) 利用 SDO/HMI 矢量磁场数据计算了 NOAA1115 活动区在 2011 年 2 月 11 - 15 日之间的磁螺度及能量谱。磁螺度的符号在所有波数上都是以正为主导, 与理论预期的符号一致, 相对磁螺度为 4%, 且在波数 $k \approx 0.4 \text{ Mm}^{-1}$ 处达到最大。相对电流螺度也有类似的符号及值。在大波数处磁螺度谱的模数为 $k^{-11/3}$ 幂律, 表示电流螺度的谱为 $k^{-5/3}$, 磁能量也存在 $k^{-5/3}$ 谱。

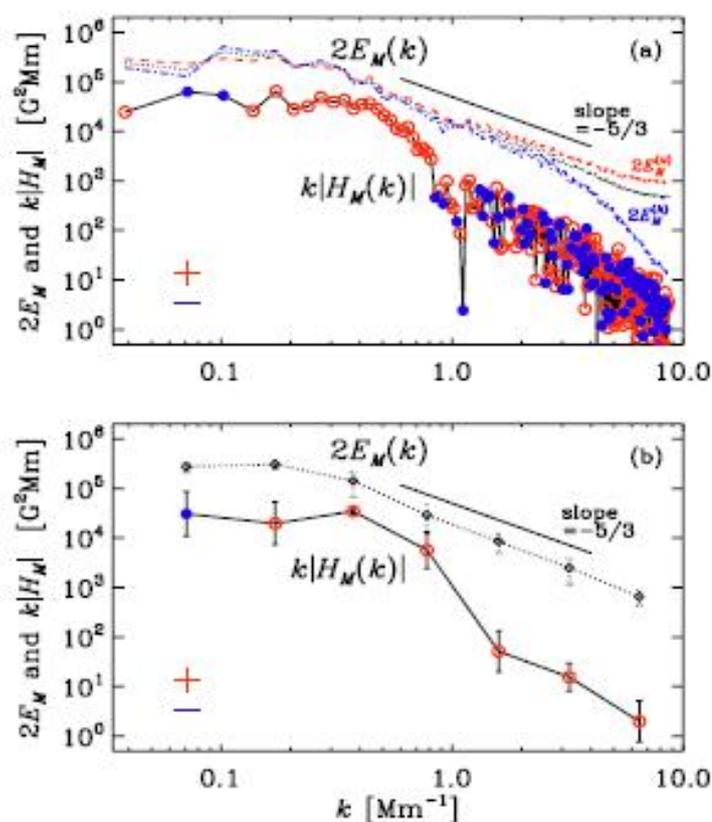


Figure 2. (a) $2E_M(k)$ (dotted line) and $k|H_M(k)|$ (solid line) for NOAA 11158 at 23:59:54 UT on 2011 February 13. Positive (negative) values of $H_M(k)$ are indicated by open (closed) symbols, respectively. $2E_M^{(h)}(k)$ (red, dashed) and $2E_M^{(b)}(k)$ (blue, dash-dotted) are shown for comparison. (b) Same as upper panel, but the magnetic helicity is averaged over broad logarithmically spaced wavenumber bins.

图 6. 64: NOAA 11158 活动区 2011 年 2 月 13 日 23:59:54 UT $2E_k$ 与 k 的关系

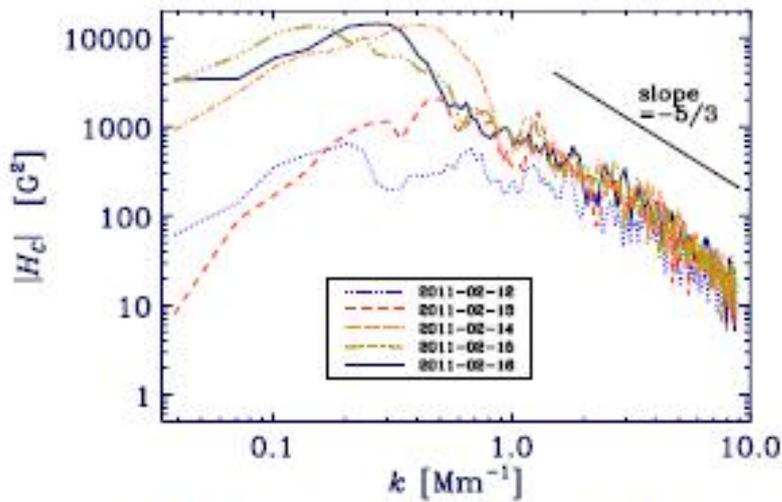


Figure 4. Unsigned current helicity spectrum, $|H_C(k)|$.

图 6.65: 电流螺度谱

6.2.25. 来自 11158 活动区 CME 的偏转与旋转

2011 年 2 月 13-16 日之间, 从 11158 活动区内的多重极性翻转线爆发了一系列 CME 事件, Kay 等 (2017, *Solar Physics*, 292, 78) 基于 STEREO-EUV 及日冕仪图像数据, 利用累进圆柱筒(GCS)通量绳模型来决定 CME 的轨迹, 然后利用被称为对磁力驱动非径向 CME 预报 CME 的轨迹改变 (ForeCAT)模拟 7 个 CME 的偏转及旋转, 发现 ForeCAT 结构与重建的 CME 位置及方向非常一致, CME 的偏转在 10 到 30 度之间。所有 CME 都向北偏转, 但还有径向方向的偏转, 顺时针及逆时针方向转动范围在 5 到 50 度之间。有 3 个 CME 开始位置在 2 度以内, 它们主要朝北偏, 稍有点偏东, 逆时针转动, 但最后它们相差了 20 到 30 度, 在方向及转动的变化来自于 CME 接近太阳的差异及径向传播, 以及 CME 质量。最终, 7 个 CME 中只有一个在地球附近产生了可分辨的特征, 尽管在整个爆发过程中, 活动区都之下地球。因此, CME 在偏转及旋转方面的差异可以解释 CME 是否影响或错过地球。

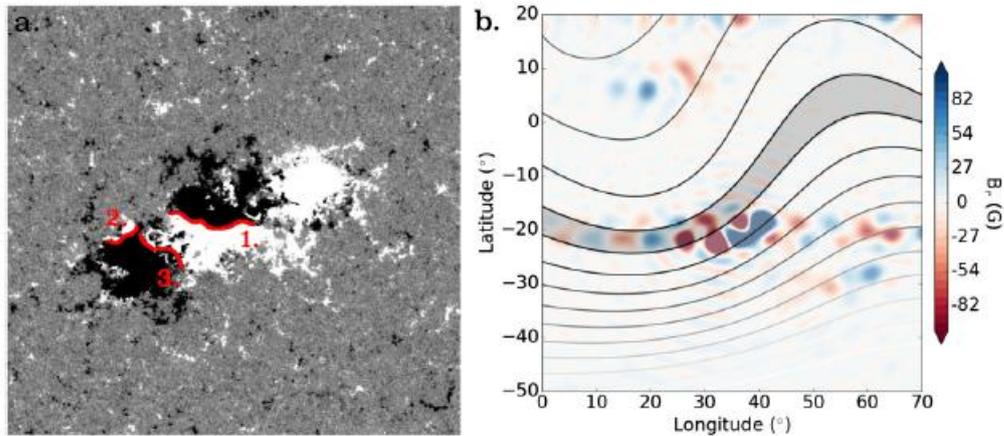


Figure 1 The left panel shows an image of AR 11158 from HMI from 14 February 2011 at 03:30 UT. The red lines indicate the three different PILs. The right panel shows the results of a potential field source surface (PFSS) magnetic field model with color regions of the surface magnetic field near AR 11158 (at $1 R_S$) and line contours of the magnetic field farther out ($2.5 R_S$) projected onto the solar surface. The gray region indicates the location of the heliospheric current sheet, approximated by the location of the weakest magnetic field strength. Panel b shows a much larger field of view than panel a with the AR in the HMI magnetogram corresponding to the enhanced magnetic field in the center of the color regions of the surface PFSS magnetic field.

图 6. 66: AR 11158 活动区 HMI 图 (2011 年 2 月 14 日 03:30 UT, 左) 及势场源表面(PFSS) 磁场模型

Figure 2 CCS reconstructed positions for CMEs 13B (top), 14A (middle), and 14C (bottom). The time corresponding to the first and last measured positions are shown on the left and right in the panels, respectively. The left column shows STEREO A/EUVI images and the right shows STEREO A/COR1 images with EUVI images in the center. STEREO A was located 87° west of the Earth during the observations. The red wireframe shows the CCS reconstruction of the CME at each height.

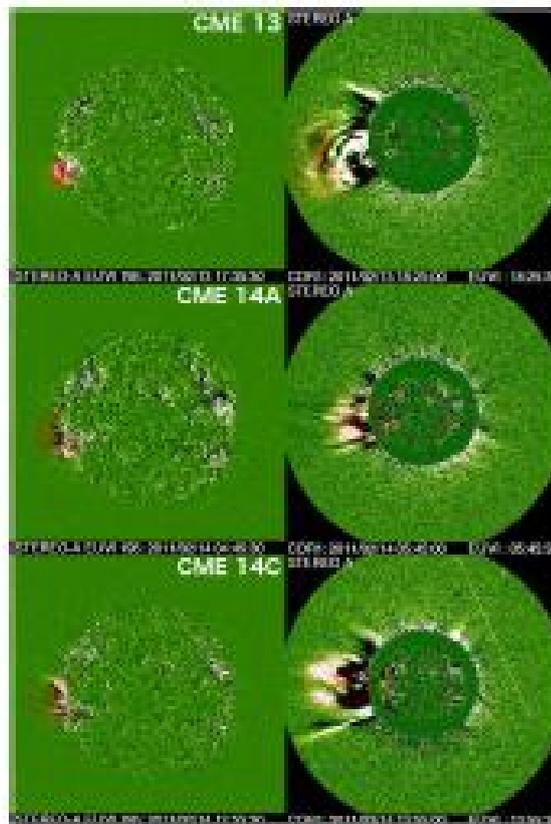


图 6. 67: STEREO A/EUVI (左) 及 STEREO A/COR1 (右) 观测图

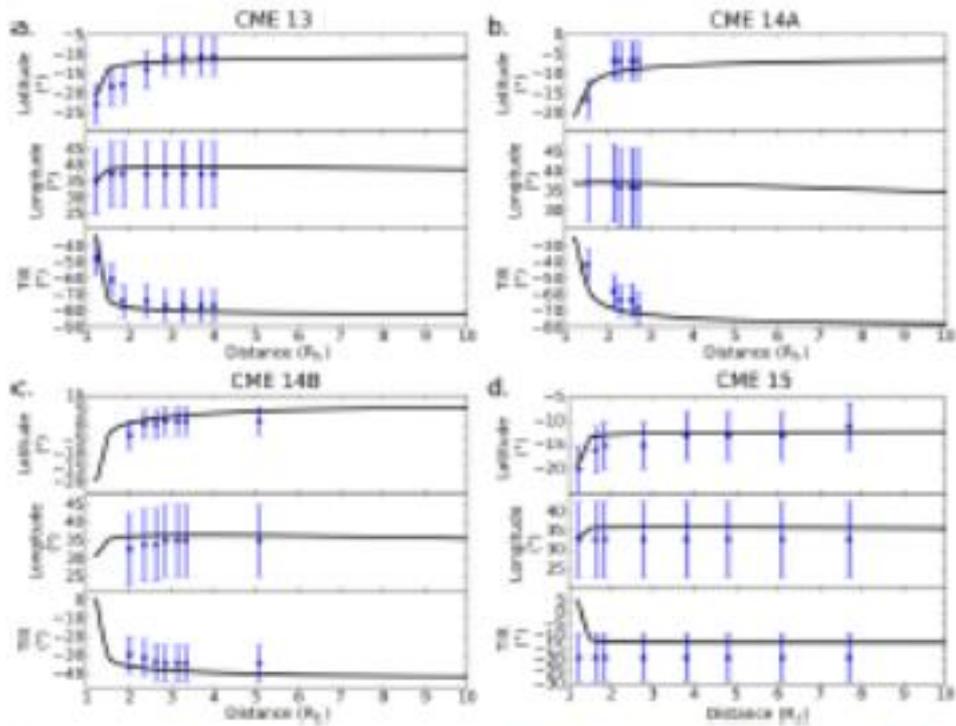


Figure 5. Comparison of the positions (latitude and longitude) and orientations of the reconstructed CMEs (blue circles) with the ForeCAT results (black lines) for four of the CMEs.

图 6. 68: 重建 CME 与 ForeCAT 结构的位置 (纬度及经度) 与方向比较

Figure 6. A side and fixed view comparing the trajectories of the seven CMEs out to $6 R_{\odot}$. We use the same colors for the three CMEs as in Figure 5. The surface of the Sun is colored according to the radial magnetic field strength from HMI. A movie version is available in the online supplementary material.

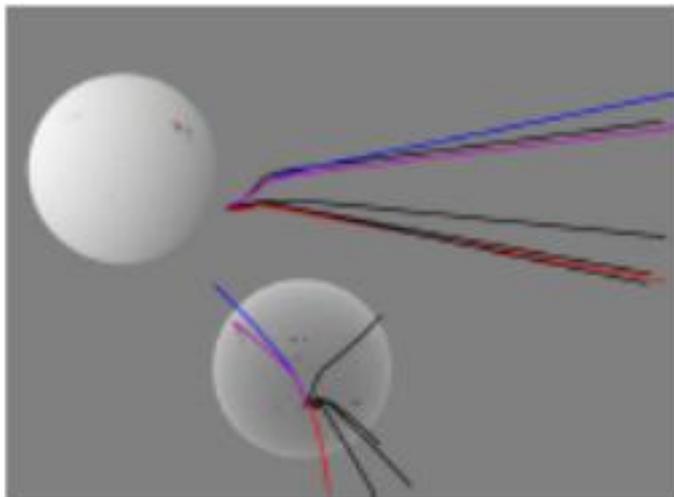


图 6. 69: CME 传到 6Rsun 时的轨迹

6.2.26. 同源耀斑—CME 事件及其与米波 II 型射电暴的联系

Yashiro 等 (2014, AdSR, 54, 1941-1948) 分析了 NOAA 11158 活动区在经过日面期间产生的耀斑与 CME 的关系, 至少有两个耀斑是同源的: 2011 年 2 月 14 日 06:51 UT 时的 C6.6 耀斑与 12:41 UT 的 C9.4 耀斑, 两耀斑发生在相同位置 (活动区的东边缘) 并且有相似的 GOES 软 X 射线衰变光变曲线, 相关的 CME 比较慢(334 和 337 km/s) 且有相似的视宽度 (43 度和 44 度), 但射电特征不同, 第二个事件与 II 型米波射电暴相关, 而第一个则没有。STEREO/COR1 日冕仪清楚地显示第二个 CME 传播到早 50 分钟的前面 CME 内。这些观测意味着 CME-CME 相互作用可能在激发由慢 CME 引起的 II 型射电辐射时起了关键作用。

表 6. 4: 2011 年 2 月 14 日 7 个爆发事件

Table 1
Seven eruptive events on 2011 Feb 14.

Label	X-ray flare			EUV wave		CME		Type II
	Time	Intensity	Location	Time	Speed ^a	Time	Speed ^b	
-	02:35	C1.6	S21E04	02:42	523	02:55	264	No
1P	04:29	C8.3	S20W01	04:44	~500	04:55	312	No
1	06:51	C6.6	S21E02	06:56	632	07:05	334	No
2P	11:51	C1.7	S21W01	12:14	~500	12:15	273	No
2	12:41	C9.4	S21W02	12:50	661	13:05	337	Yes
-	17:20	M2.2	S20W04	17:28	800	17:35	507	Yes
-	19:23	C6.6	S20W05	19:31	495	19:45	355	No

^a EUV wave speed in km/s.

^b CME speed in km/s.

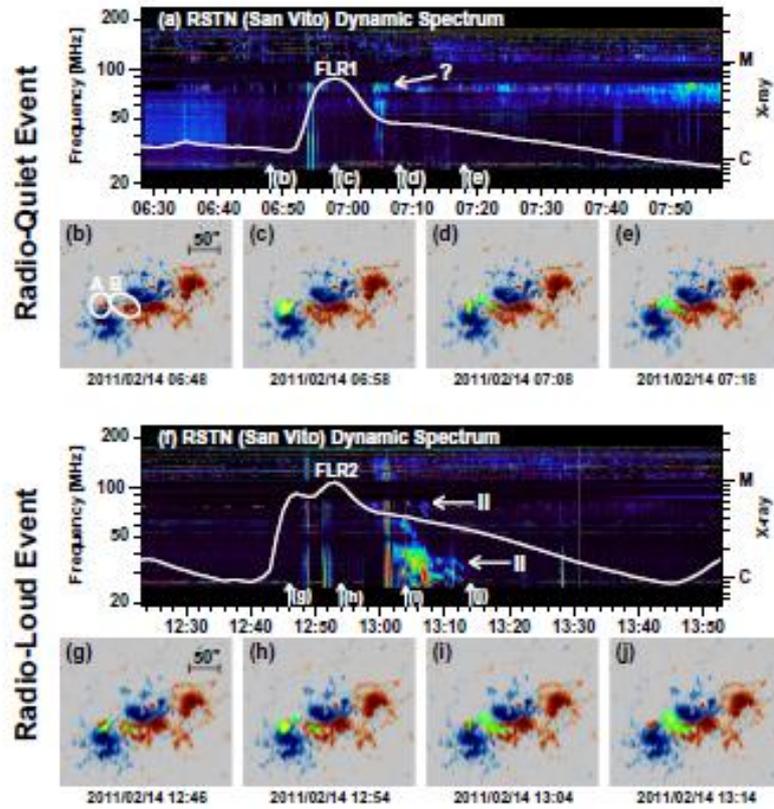


Fig. 1. (a, f) Radio dynamic spectrum observed by the San Vito Solar Observatory of the Radio Solar Telescope Network (RSTN). The observed frequency range is from 25 to 180 MHz. The white curve shows the GOES X-ray intensity in the long-wavelength band. The peak X-ray intensity was C6.6 for the first flare (FLR1) and C9.4 for the second flare (FLR2). (b-e, g-j) Magnetogram images observed by SDO/HMI. Red and blue color correspond to positive and negative polarities. The overlaid green images were the SDO/AIA 94 Å observations, indicating the location of FLR1 and FLR2.

图 6. 70: RSTN 观测的射电动力谱 与 GOES 流量(a, f), 第一个是 C6.6(FLR1) 第二个是 C9.4 (FLR2)耀斑, (b - e, g - j) SDO/HMI 磁图

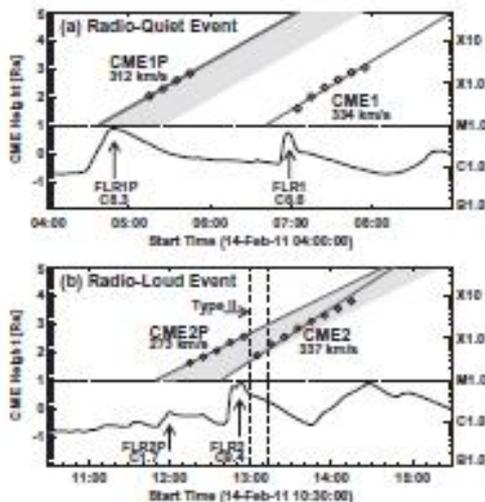


Fig. 4. CME height-time plots (diamonds) and GOES X-ray light curves for the (a) radio-quiet and (b) radio-loud event. The duration of the metric type II radio burst is indicated by the dashed lines. All flares noted in the plots occurred at the same location in AR 11158. The CME heights are measured from the center of the Sun in solar radii (R_{\odot}), i.e., the solar limb corresponds to $1 R_{\odot}$. The shadows under CME1P and CME2P represent their thickness, showing that CME2 propagated into CME2P around the onset of type II burst.

图 6. 71: 无射电(a)及强射电 (b)事件 CME 高度-时间图

6.3. 主要科学贡献

● 多波段成像综合分析研究

➤ SDO/AIA 观测的冕环及活动区自动温度及辐射测量分析

发展了一种数字编码用来自动分析 SDO/AIA 图像数据，包括：i)不同波段的对齐；ii)自校准；iii) 自动产生微分辐射[DEM] 分布；iv) 活动区或小面积的 DEM 分布组合；v)自动检测冕环；vi)自动去除背景及对冕环的热分析，对冕环温度、温度宽度、辐射量 [EM]、电子密度及环宽度进行统计。

➤ 日冕磁场外推-CESE - MHD - NLFF 码

用 MHD 松弛法发展了一新 NLFFF 模型来重建日冕磁场，这种方法基于 CESE - 具有保护元/解决元空时方案的 MHD 模型。

● 物理现象及参量研究

➤ 大爆发活动区的磁场及能量演化

非线性无力场外推日冕磁场显示，在暗条通道中处于低位的千高斯剪切场的 S 性暗条附近早期通量浮现期间，有大量的电流及自由能增加，磁自由能的最大值达到了在 6Mm 以下储存值的 50%左右，在 X 耀斑的一个小时内的减少很可能低估了实际能量损失。耀斑期间光球场快速变化：在核心区水平场提高了 28%，变得更倾斜、更与极性翻转线平行，这种变化与推测的日冕场“爆炸”一致。在耀斑之后，外推场变得更加“紧致”，可能是由于重联的原因在核心区环较短，在最低层，日冕场变得更剪切。

➤ 光球磁场耀斑的响应

发现磁翻转线(PIL)的水平磁场快速 (30 minutes)且不可逆的增强 (~30%)，光球磁场变得更加剪切与倾斜。场演化与 S 型活动区的耀斑发生相关，增强的面积位于两个色球耀斑带与初始共轭硬 X 射线足点之间，在爆发之后，PIL 附近的磁力线更水平，与 tether-cutting 重联新形成的下方场有关。

➤ TETHER-CUTTING 重联及磁内爆之后光球磁场的快速变化

SDO/HMI 探测到的快速变化位于磁 S 型中心的紧致区，平均水平磁场强度

增加了 28%。该区域位于色球起始强 UV 和硬 X 射线源之间，与 NLFFF 模型 S 型中心足点重合。NLFFF 模型还显示强日冕电流集中在该区域上方，在 S 型爆发之后，日冕电流系统经历了明显的向下塌缩。这些结果支持产生耀斑的 tether-cutting 重联及由能量释放导致的日冕场内爆。

➤ 六个大中性线耀斑光球磁场与洛伦兹力矢量的突变

在 SDO/HMI 观测的四个活动区 NOAA 11158, 11166, 11283 和 11429 产生的六个大耀斑期间，中性线场矢量变得更强、更水平，几乎都是由与中性线平行的水平场分量拉伸的结果。耀斑前中性线场比势场线更垂直，在耀斑期间突然塌缩且永久地靠近势场倾角。与参考势场的剪切角并没有显示这种形态。与耀斑前相比，塌缩场更倾向于与中性线对齐。在耀斑期间，垂直洛伦兹力由一个大的、突然的、永久的向下变化，与环塌缩一致。水平洛伦兹力在中性线两侧以相反的方向场中性线平行，是耀斑期间场收缩的特征。耀斑对场倾角比剪切更大的影响可由光球线捆 (line-tying) 解释。

➤ 耀斑期间日冕和光球内磁场塌缩证据

在 NOAA 11158 事件中识别出了冕环动力行为三个明显的相位：(1)慢上升相位：耀斑前环顶慢的上升运动，(2)塌缩相：环顶的突然收缩，较低的环境塌缩的比较高的环要早；(3)震动相：在塌缩相之后，环显示在不同周期的全球 kink 震动周期随环高度的减少而减少。耀斑后纵向磁图在沿着 PIL 相干斑上方显示磁通阶跃式的永久减少现象。通过分析该斑上方 HMI Stokes 参量，发现耀斑后 V 分量系统地减少，而 Q 及 U 分量增加。这些观测提示耀斑之后，靠近 PIL 的磁场形状变得更加水平。

➤ 具有日冕零点的四极磁场中的非径向爆发

报道了 NOAA11158 活动区一个同源非径向爆发事件，被局部磁场强烈调制，在复杂黑子中浮现了一个小偶极子，跟着产生了一个四极通量系统。从非线性无力场外推看到，快速剪切偶极子仅仅在一天就积累了活动区 10% 的自由能量，而其磁通仅仅占 5%。在爆发期间，喷出的等离子体高度倾斜，与径向夹角超过 60 度，形成了一个喷气形状、到 Y 型结构。

➤ X2.2 白光耀斑的速度与磁场瞬变

耀斑峰值期间，探测到磁场与多普勒速度 (DV) 瞬变现象出现在主黑子本

影边界处。这些瞬变现象持续了几分钟，在空间与时间上与耀斑核对应，瞬变处的磁场极性翻转，同时 DV 增加，这些变化在斯托克斯所有参量中都有反应。

➤ X2.2 耀斑的突然光球运动与黑子旋转

利用微分放射速度估计方法和傅里叶局部相关跟踪方法，计算了 NOAA 11158 活动区光球流动的速度和涡度，并分析了其时间演化。结果显示，磁极性翻转线周围的剪切流突然降低，在耀斑脉冲相期间旋转运动突然变化。这些结果可由 Hudson 等和 Fisher 等提出的洛伦兹变化解释。

➤ NOAA 11158 活动区的耀斑与磁非势性

与磁通相比，磁非势性与耀斑关系紧密，浮现通量区对理解磁非势性与耀斑非常重要。(1)源场中的涡旋直接显示水平磁场的偏转，旋转对应延迟的快速旋转黑子，黑子旋转导致非势增加；(2) 矢量磁场方位角具有明显变化的两个区域是在磁极性翻转线附近；(3) 4 个耀斑期间螺度快速变化且明显增强。

● 运动与机制研究

➤ 耀斑、带、冕峰及物质抛射：MHD 通量绳模型

从 11158 活动区中心 δ 黑子群之间的剪切极性翻转线上方的通量绳结构可以看到膨胀环，最终形成 CME 运动到日球内部。观测支持如下解释：包括 EIT 波的这些特征是由环示踪的碰撞体，被移动的波峰包围，而不是波主导的扰动。爆发的侧面膨胀被限制在局部盔状流结构并停在相连的大规模区域边缘。AIA 观测显示等离子体加热发生在波峰内部，利用 AIA 响应函数分析，通过宁静太阳的波峰部分与绝热加热一致，其它部分需要 MHD 模型暗示的焦耳耗散等额外加热。

➤ 活动区旋转黑子的作用

发现 NOAA 11158 活动区由两个大旋转黑子组成，一个与易于产生耀斑的区域相连，另一个与 CME 相连。空时图显示黑子存在峰值旋转速度，与大爆发事件重合。平均剪切角及螺度注入率与易于产生 CME 区域的黑子旋转轮廓对应很好。在光球层由维力理论计算出的平均自由能清楚地显示在耀斑初始阶跃减少。螺度注入分布在与 CME 相关的区域是均匀的，而在与耀斑相关的区域则不是且常改变符号。

➤ 相对磁螺度与电流螺度的演化

X2.2 耀斑之前两天内电流螺度密度向上传播，传播与进入到光球的磁浮现同时，及 X2.2 耀斑的能量逐渐积累。相对磁螺度的时间轮廓显示单调上升，而在耀斑前由升降变化，这种形态明显地存在于磁螺度中而没有存在于磁通量中。

➤ 与 X2.2 耀斑相关的快速黑子旋转

11158 活动区由 4 个浮现的偶极场构成，造成复杂的黑子运动，前面的偶极黑子运动最快，不仅通过另一偶极后随端，从而引起剪切运动，而且还与同极性的黑子混合形成单一的大本影，这样导致形成一个 S 形状的 δ 黑子，在其上形成 EUV 暗条通道和 S 形态，进而爆发产生耀斑。耀斑前 20 小时，随着顺时针 (CW) 螺旋半影暗条形态的发展，混合的黑子开始快速绕本影中心顺时针旋转。旋转持续整个耀斑期间但在耀斑结束之后 1 小时突然停止，且保持扭曲半影暗条形状。

➤ MHD 模拟：与观测比较

发现 NLFFF 从来没有显示观测看到的引人注目的动力学行为，即它是稳定状态而不是扰动。另一方面，MHD 模拟显示，当在中性线附近形成强剪切线时，它们最终会通过复杂重联从太阳表面爆发掉。这种结果支持如下论点，在 NLFFF 通过 tether-cutting 重联形成的强剪切线负责打破磁场在底日冕力的平衡条件。

➤ 触发 NOAA11158 活动区 M6.6 耀斑的磁场系统

发现 NOAA11158 活动区的 M6.6 耀斑由两个大浮现偶极子构成，在这个四级活动区中心，通过的磁元的自行运动形成高剪切的极性翻转线(PIL),在 PIL 上方形成剪切的冕拱。观测支持这样的解释，目标耀斑由具有入侵结构（正极性穿入负极性）的磁场局部区域触发。发现触发区域的形成是由小规模磁场快积累导致。在触发耀斑活动的过程中，包括各种规模的所有磁系统，不仅包括整个活动区演化，还包括磁场精细结构。

➤ 耀斑的触发过程研究

发现磁剪切角都超过了 70 度，在耀斑前相就发生了磁场扰动：一类是反极性，另一类是反剪切，非常小的磁场扰动也可能触发大的耀斑。

➤ 产生 11158 活动区 X 和 M 级耀斑的磁结构

利用非线性无力场外推方法，发现在 M6.6 和 X2.2 耀斑前从半圈到一圈的强扭曲场线，在耀斑后消失，保持到耀斑之后的大部分 twist 小于半圈。在 M1.0

和 M1.1 耀斑前也建立了强扭曲，大部分保持到之后。强扭曲线大多被弱扭曲线包围，后者与正黑子的顺时针运动一致，足点根植于强磁场区。

➤ 日震动耀斑的磁声能研究

基于 DSO/HMI 多普勒图数据用局部日震学方法识别 11158 活动区的震动源，用 RHESSI 硬 X 射线数据来检测耀斑期间震动源的位置与粒子沉降点的关系。洛伦兹力对太阳震动贡献相当大。可是，也有这样的区域，洛伦兹力很强，但并没有明显的声辐射。

➤ NOAA 11158 活动区磁拓扑的时间演化

通过计算挤压程度因子 Q ，得出的准分割层(QSL) 显示这个活动区有一个由磁四极子形成的全局拓扑，包括一个相当稳定的双曲通量管 (HFT)结构。强 QSL 与高剪切拱对应，与通量绳的形成有关。在 M6.6 和 X2.2 耀斑刚开始前 QSL 非常突出，这意味着强 QSL 与 11158 活动区的高耀斑产率存在密切的关系。此外，在 X2.2 耀斑前 QSL 上方发现一个小的反泪珠 HFT 结构，说明这个地方存在磁通量绳。在爆发期间全局构型 (HFT)仅起次要作用。

➤ 两个活动区在光球及光球下的水平流动

AR11084 活动区在两层发现有相似的结构：黑子本影内的向内流动及包围黑子的向外流动。内流与外流的边界（两层稍有差别）在黑子半影内，在光球下内流的面积比光球内流面积稍大。对于 AR11158 活动区来说，在有些区域这两层的流动非常相似，而在另外区域差异巨大，在包围黑子的区域，两层都显示一致的外流。此外，在光球看到的与通量浮现相关的多数流动特征在光球下并没有响应的对应物，这意味着由通量浮现引起的水平流动并没有延伸到光球下。

➤ 活动区的磁螺度及能量谱

磁螺度的符号在所有波数上都是以正为主导，与理论预期的符号一致，相对磁螺度为 4%，且在波数 $k \approx 0.4\text{Mm}^{-1}$ 处达到最大。相对电流螺度也有类似的符号及值。在大波数处磁螺度谱的模数为 $k^{-11/3}$ 幂律，表示电流螺度的谱为 $k^{-5/3}$ ，磁能量也存在 $k^{-5/3}$ 谱。

● 射电研究

➤ 与耀斑相关的 III 型射电暴 EUV 喷流的动力学行为

Wind/WAVE 及地面射电望远镜阵观测到的 III 型射电暴与 SDO/AIA 及 RHESSI 观测的 EUV 喷流 (jet) 及硬 X 射线辐射在时间上吻合, 显然 EUV jet 与硬 X 射线辐射有共同的源区, III 型辐射与 jet 足点热的 (7MK) 等离子体有关。

➤ 同源耀斑—CME 事件及其与米波 II 型射电暴的联系

分析了 NOAA 11158 活动区在经过日面期间产生的耀斑与 CME 的关系, 至少有两个耀斑是同源的: 2011 年 2 月 14 日 06:51 UT 时的 C6.6 耀斑与 12:41 UT 的 C9.4 耀斑, 两耀斑发生在相同位置 (活动区的东边缘) 并且有相似的 GOES 软 X 射线衰变光变曲线, 相关的 CME 比较慢(334 和 337 km/s) 且有相似的视宽度 (43 度和 44 度), 但射电特征不同, 第二个事件与 II 型米波射电暴相关, 而第一个则没有。STEREO/COR1 日冕仪清楚地显示第二个 CME 传播到早 50 分钟的前面 CME 内。这些观测意味着 CME-CME 相互作用可能在激发由慢 CME 引起的 II 型射电辐射时起了关键作用。

● CME 特性及其传播

➤ 来自 11158 活动区 CME 的偏转与旋转

利用累进圆柱筒(GCS)通量绳模型来决定 CME 的轨迹, 然后利用被称为对磁力驱动非径向 CME 预报 CME 的轨迹改变 (ForeCAT)模拟 7 个 CME 的偏转及旋转, 发现 ForeCAT 结构与重建的 CME 位置及方向非常一致, CME 的偏转在 10 到 30 度之间。所有 CME 都向北偏转, 但还有径向方向的偏转, 顺时针及逆时针方向转动范围在 5 到 50 度之间。有 3 个 CME 开始位置在 2 度以内, 它们主要朝北偏, 稍有点偏东, 逆时针转动, 但最后它们相差了 20 到 30 度, 在方向及转动的变化来自于 CME 接近太阳的差异及径向传播, 以及 CME 质量。最终, 7 个 CME 中只有一个在地球附近产生了可分辨的特征, 尽管在整个爆发过程中, 活动区都之下地球。

6.4. 其它

6.4.1. 其它参考文献

参见第五章 5.2.5.2.19 NOAA 10930 和 11158 耀斑的触发过程研究, p.177

6.4.2. 观测影像资料

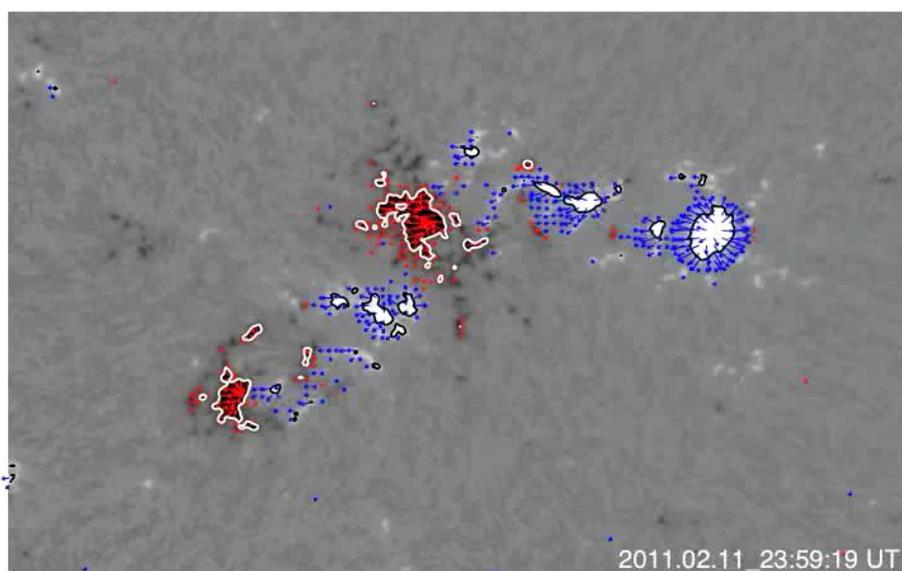


图 6.72: 2011 年 2 月 14 日 20:35 UT AR11158 耀斑前 5 小时 SDO/HMI 观测的 NOAA11158 活动区矢量场 ([Sun, 2012, APJ, 748, 77](#))

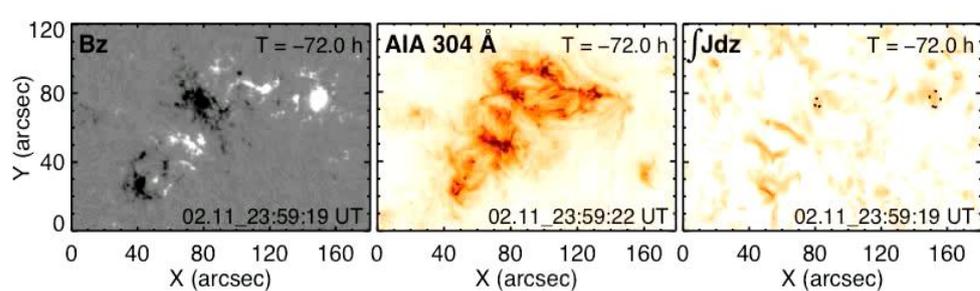


图 6.73: AR11158 的 HMI B_z (左)、AIA 304 (中) 及 NLFFF 计算的垂直电流积分 (右) ([Sun, 2012, APJ, 748, 77](#))

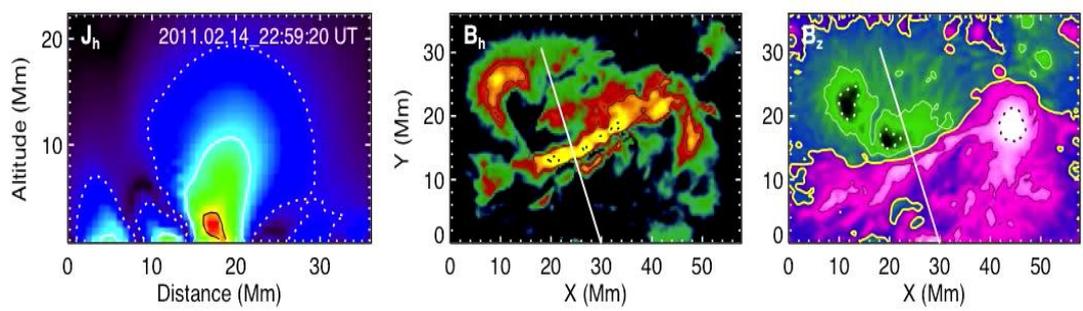


图 6. 74: 2011 年 2 月 15 日 01:35:20 UT NLFFF 计算 NOAA11158 水平电流密度、水平场及垂直场 ([Sun, 2012, APJ, 748, 77](#))

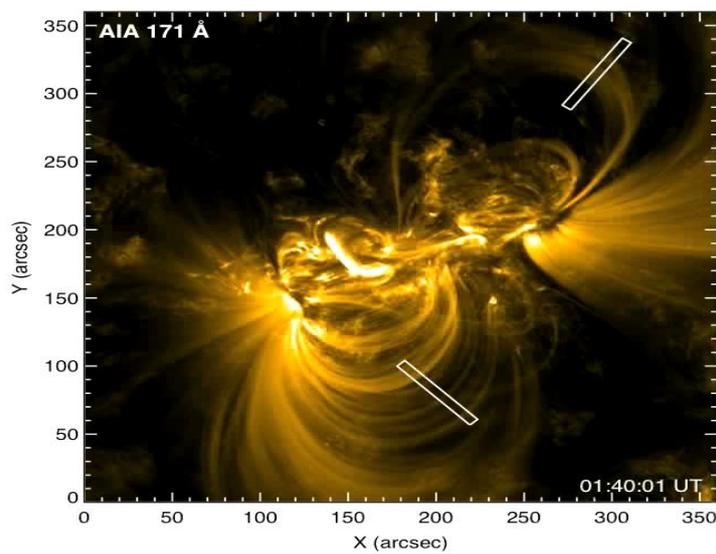


图 6. 75: 2011 年 2 月 15 日 01:48:01 UT AIA 171 Å 对 NOAA11158 冕环观测 ([Sun, 2012, APJ, 748, 77](#))

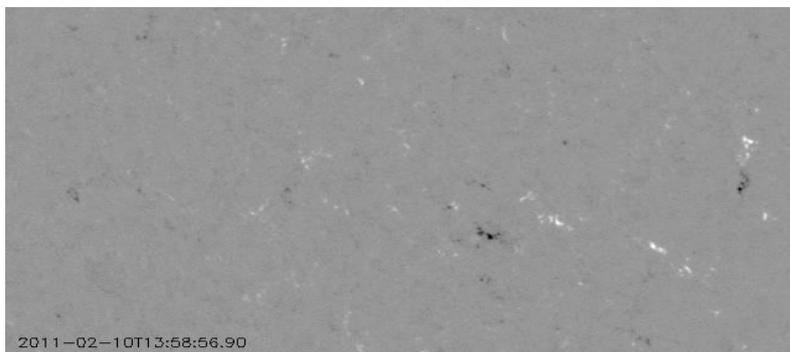


图 6. 76: 2011 年 2 月 10 日 14 UT HMI 观测的 NOAA11158 耀斑前矢量磁图 ([Schrijver, 2011, APJ, 738, 167](#))

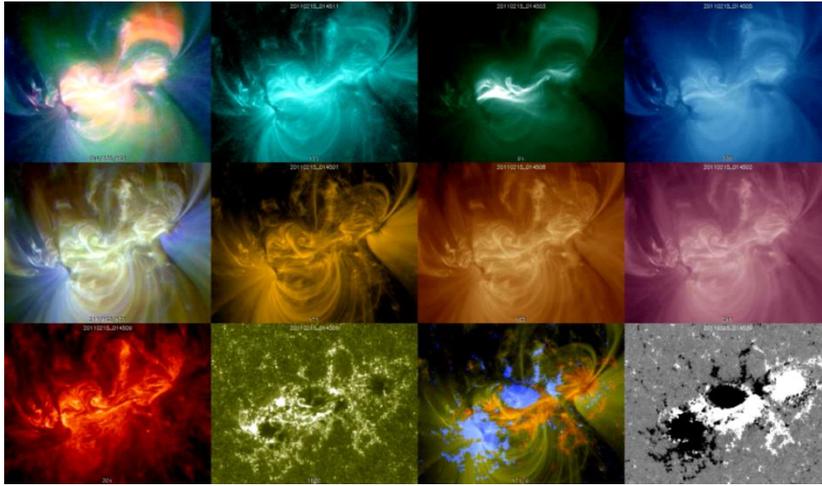


图 6. 77: 2011 年 2 月 15 日 01:46:56 UT AIA 观测的 NOAA11158 图([Schrijver, 2011, APJ, 738, 167](#))

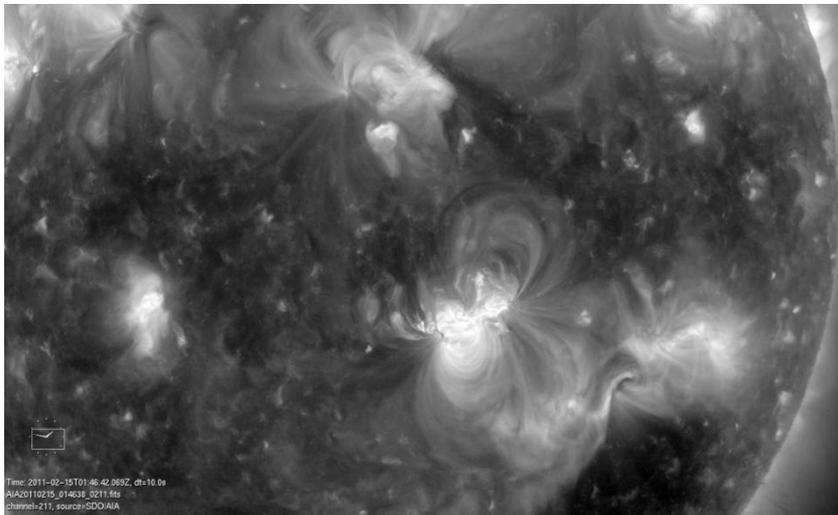


图 6. 78: 2011 年 2 月 15 日 01:46 UT SDO/AIA 211Å 观测的 NOAA11158 图([Schrijver, 2011, APJ, 738, 167](#))

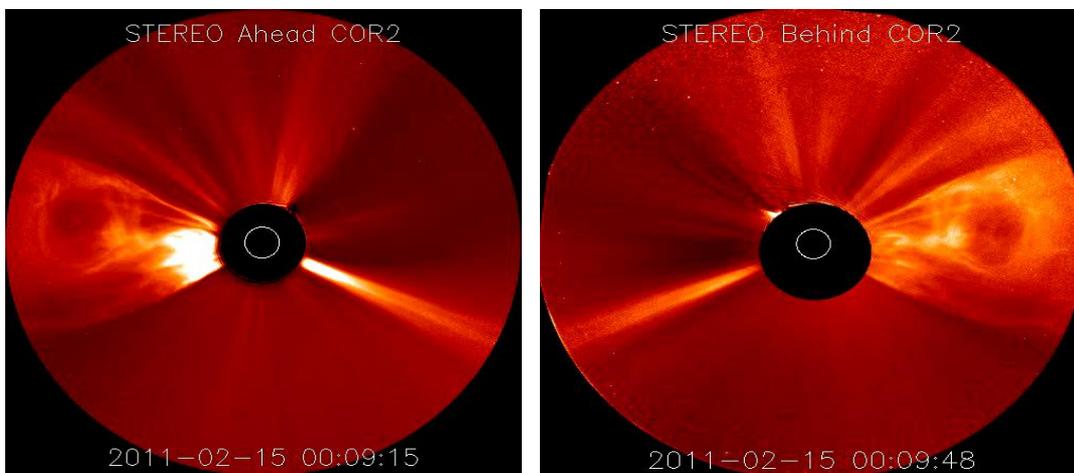


图 6. 79: 2011 年 2 月 15 日 STEREO A、B/COR2 观测到的 CME([Schrijver, 2011, APJ, 738, 167](#))

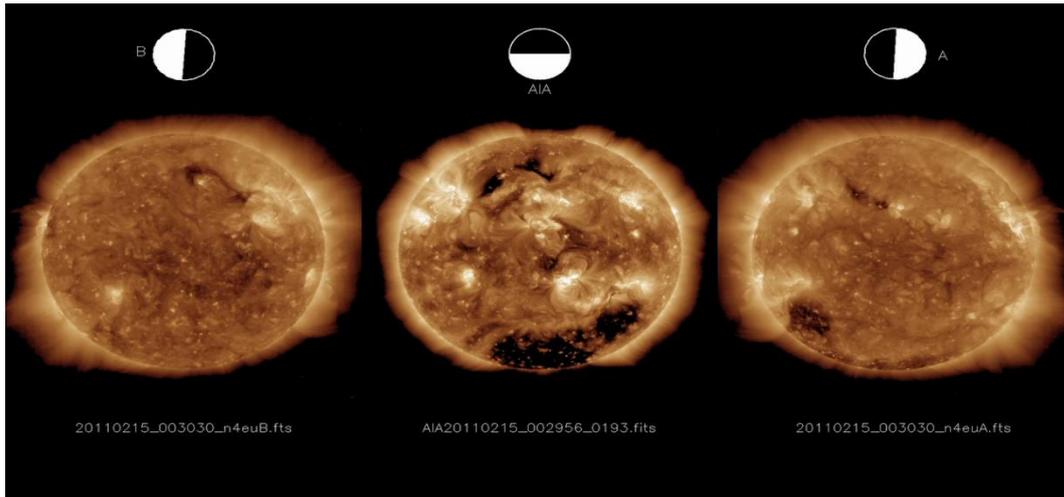


图 6. 80: 2011 年 2 月 15 日 STEREO 观测到的 CME 差分图 ([Schrijver, 2011, APJ, 738, 167](#))

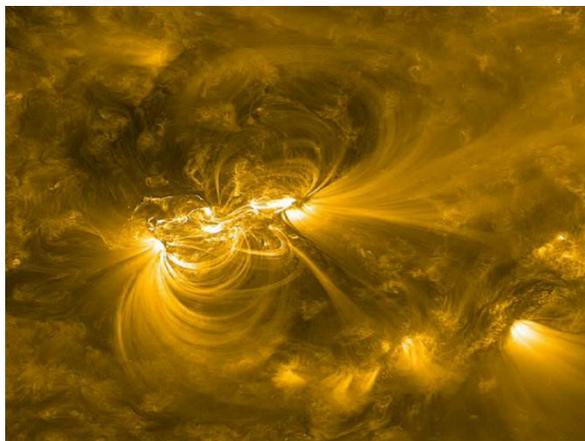


图 6. 81: 2011 年 2 月 15 日 2:29 UT SDO/AIA Feix 171Å观测到的 NOAA11158 活动区([Gosain, 2012, APJ, 749, 85](#))

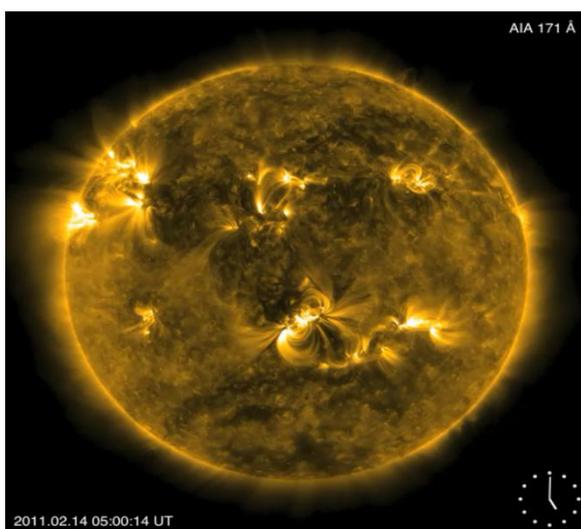


图 6. 82: 2011 年 2 月 14 日 17:28:15 UT AIA 171Å显示 NOAA11158 活动区非径向爆发 ([Sun, 2012, APJ, 757, 149](#))

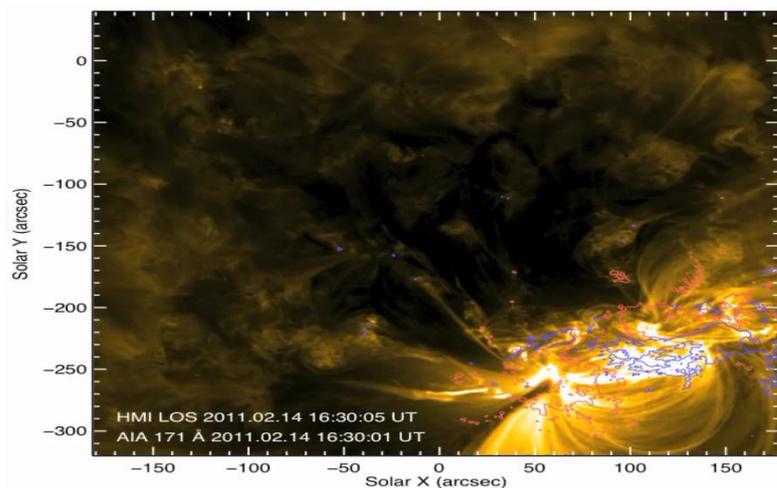


图 6. 83: 2011 年 2 月 14 日 17:28:15 UT AIA 显示 NOAA11158 活动区非径向爆发的几何形状 ([Sun, 2012, APJ, 757, 149](#))

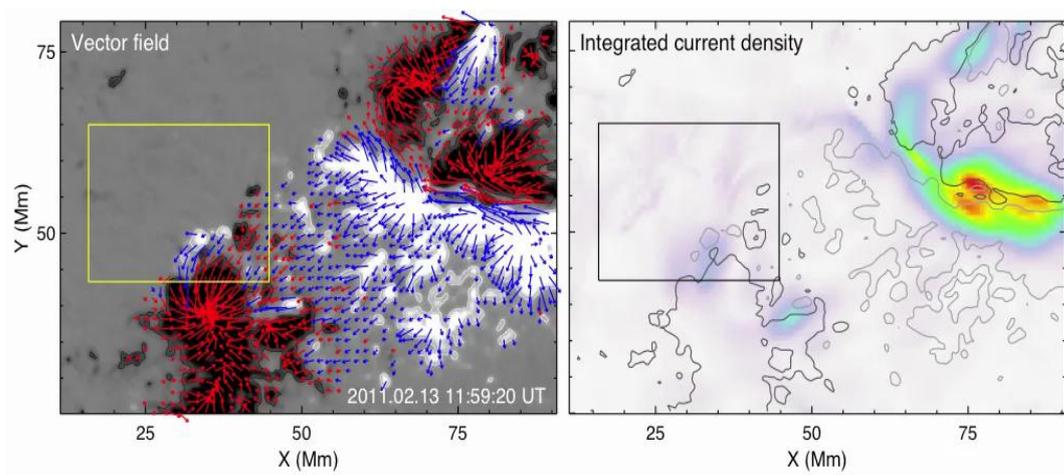


图 6. 84: 2011 年 2 月 14 日 AR 11158 爆发前 25 分钟的磁场与电流密度 ([Sun, 2012, APJ, 757, 149](#))

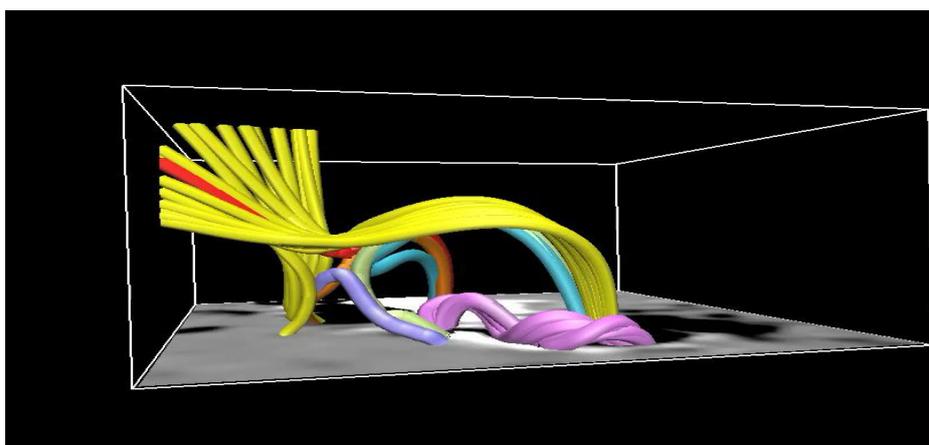


图 6. 85: NOAA11158 活动区 NLFFF 外推磁场拓扑 ([Sun, 2012, APJ, 757, 149](#))

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第七章 NOAA11429 活动区事件

7.1. 事件概述

NOAA11429 活动区于 2012 年 3 月 4 日出现在日面东边缘 (N18E68)，3 月 15 日消失日面西边缘 (N19W77)，产生了 2 个 X 级耀斑、13 个 M 级耀斑，太阳质子事件，全晕 CME，地磁暴 $Dst=-143nT$ 。

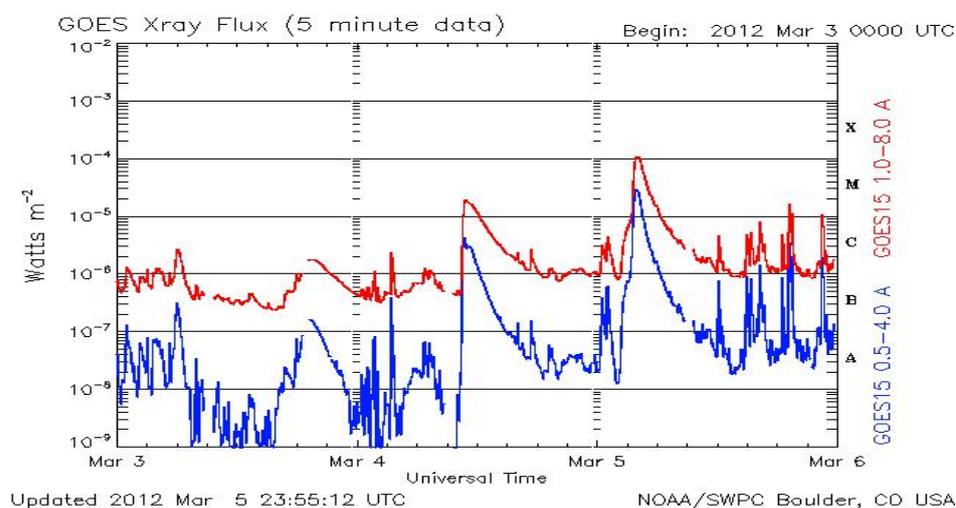


图 7. 1: GOES 流量图 (3 月 3 日到 6 日)

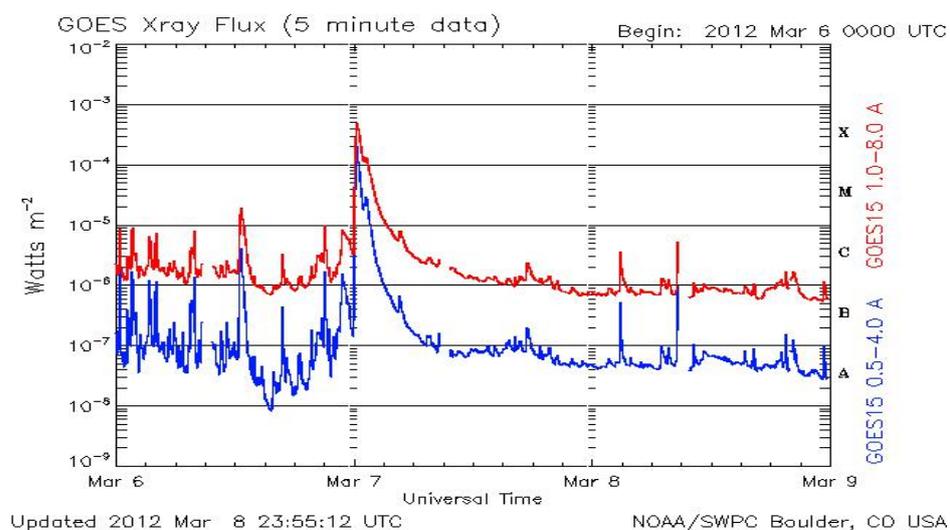


图 7. 2: GOES 流量图 (3 月 6 日到 9 日)

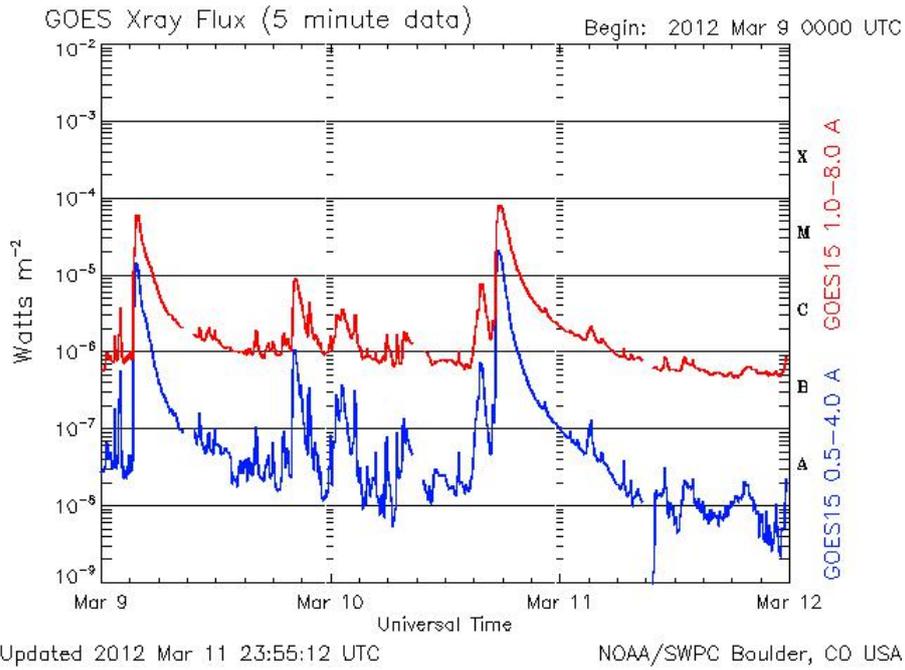


图 7. 3: GOES 流量图 (3 月 9 日到 12 日)

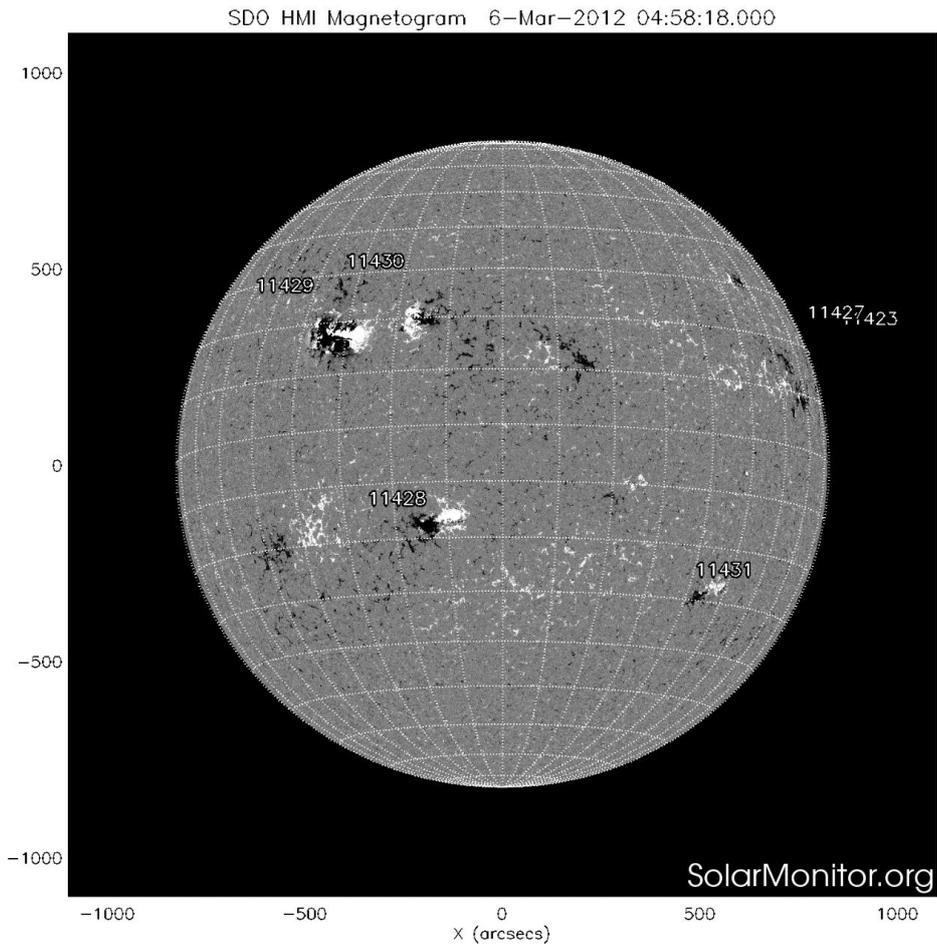


图 7. 4: SDO/HMI 磁图 (2012 年 3 月 6 日)

7.1.1. 事件特征

- 事件观测时间：2012年3月4日产生，3月15日消失
- 最大面积：1270日面单位；时间：2012年3月8日；位置：N17E15
- 磁位型： $\beta\gamma\delta$
- X级耀斑数量：2
- M级耀斑数量：13
- C级耀斑数量：32
- 最大耀斑级别：X5.4；时间：2012年3月7日00:17UT；位置：N17E27
- 太阳质子事件：6530 pfu
- 高能粒子事件：质子事件
- CME事件：全晕CME
- 对地效应：地磁暴（Dst=-143nT），kp=7(3月9日)

7.1.2. 观测特征

2012年3月5日三个CME之间引起了相互作用，在地球附件观察到了一族激波事件及行星CME事件，产生了高能粒子事件及大磁暴（Dst=-143nT）。

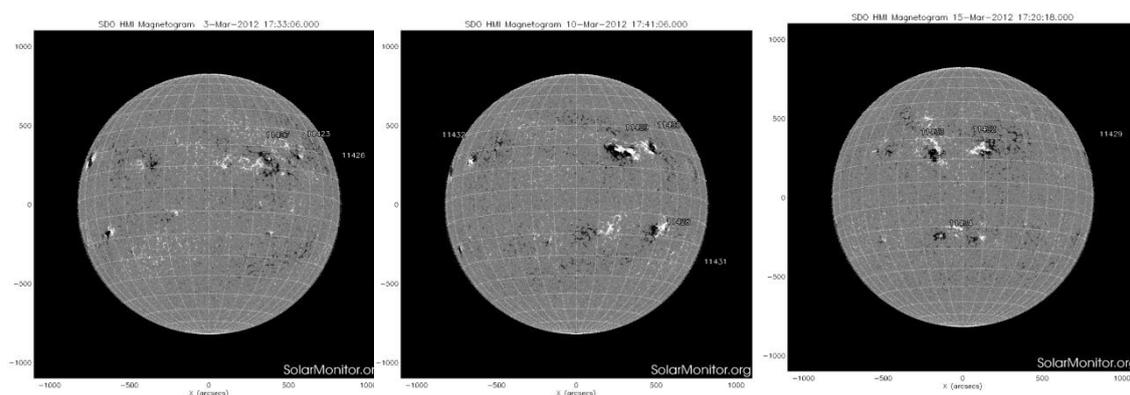


图 7.5：2012年3月3日-15日 SDO/HMI 全日面磁图

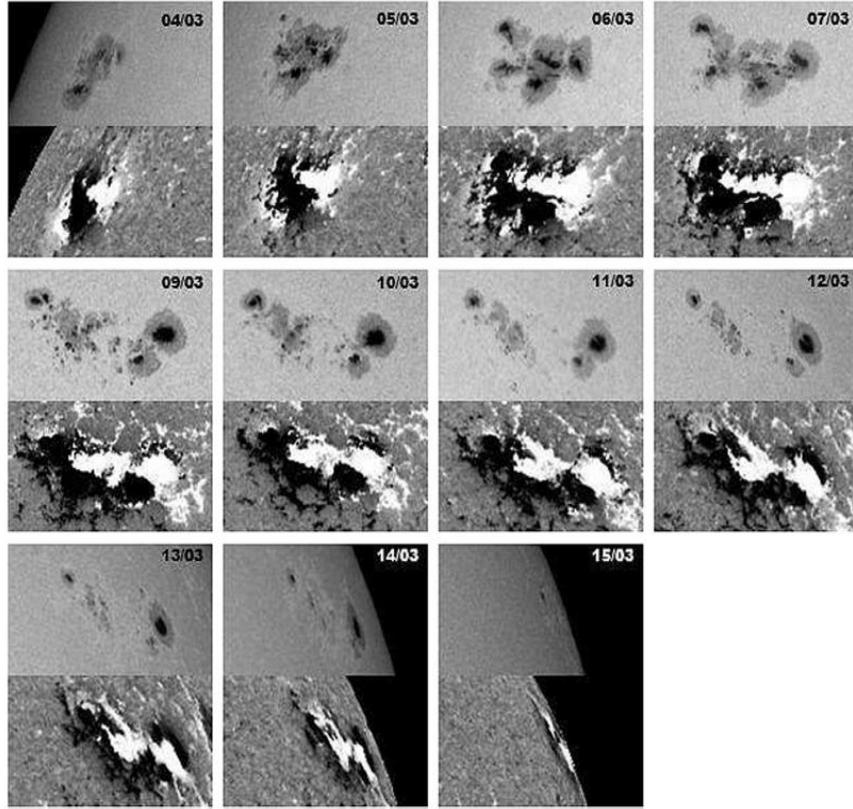


Fig. 3. The evolution of the active region NOAA AR 11429 close-up view, during the period March 04–15, 2012; intensitygrams (upper panels; KSU local data) and line-of-sight magnetograms (lower panels; SDO/HMI images). Positive flux is white (North polarity; outward directed), negative is black (South polarity; inward directed). North is up and west is to the right. The corresponding dates are reported.

图 7. 6: 黑子和活动区演化: KSU (上) 及 SDO/MHI (下)

表 7. 1: NOAA11429 活动区特性

Table 2

NOAA AR 11429 properties & estimated parameters.

Date (JD + 2450000)	CM ^a Location Carrington System	Magnetic class	Area (in μHem) corrected for foreshortening	Tilt-angle ^c	Sidereal ang. vel. (deg.day ⁻¹)	X-ray flares ^d	
				(deg)		X	M
03/03 ^b	-	$\beta-\gamma$	-	-	-	0	0 3
04/03 (5990.915)	21.35–300.5	$\beta-\gamma-\delta$	848 ± 100	17.65±3.5	-	0	1 3
05/03 (5991.904)	19.2–300.2	$\beta-\gamma-\delta$	1160 ± 150	13.47±2.9	-	1	3 12
06/03 (5992.887)	20.2–300.8	$\beta-\gamma-\delta$	1319 ± 150	5.834 ± 1.6	14.719	0	6 5
07/03 (5993.892)	19.15–300.5	$\beta-\gamma-\delta$	1318 ± 150	5.096 ± 1.7	13.972	1	0 1
08/03 ^b	-	$\beta-\gamma-\delta$	-	7.615 ± 1.4	-	0	0 1
09/03 (5995.927)	18.15–299.75	$\beta-\gamma-\delta$	1184 ± 100	9.0558 ± 1.4	13.698	0	1 0
10/03 (5996.905)	18.1–299.8	$\beta-\gamma-\delta$	1185 ± 100	8.03 ± 1.5	14.230	0	1 2
11/03 (5997.884)	17.55–300.3	$\beta-\gamma-\delta$	984 ± 100	5.44 ± 1.6	14.662	0	0 1
12/03 (5998.879)	18.45–299.55	$\beta-\gamma-\delta$	788 ± 80	6.77 ± 1.9	13.408	0	0 1
13/03 (5999.893)	18.4–299.4	$\beta-\gamma$	706 ± 80	5.9 ± 2.5	14.044	0	1 1
14/03 (6000.882)	19.2–299.1	β	544 ± 80	-	13.837	0	0 0
15/03 (6001.927)	-	β	-	-	-	0	0 2

^a Center of mass of the sunspot-group region.

^b Not covered by our local observations.

^c Based uniquely on SDO/HMI magnetograms.

^d Daily number of each flare-class.

表 7. 2: NOAA 11429 活动区综述

Table 1 NOAA AR 11429 activity report^a – 6 to 11 March 2012.

Event ^b [SWPC Number]	Date (March 2012)	Begin–Max–End [UT]	Particulars (Class–Flux Peak [W m ⁻²])	CME ^c ?
1530+	06	0022–0028–0031	M1.3–3.7E–03	No
1570+	06	0136–0144–0150	M1.2–5.9E–03	No
1590+	06	0226–0233–0237	C2.4–1.1E–03	No
1600+	06	0324–0328–0331	C9.2–2.2E–03	No
1630×	06	0401–0405–0408	M1.0–2.6E–03	Yes
1650+	06	0519–0528–0531	C2.9–1.4E–03	No
1690+	06	0731–0743–0747	C5.3–3.2E–03	No
1700×	06	0752–0755–0800	M1.0–2.7E–03	Yes
1750+	06	1110–1117–1122	C2.8–1.5E–03	No
1760+	06	1223–1241–1254	M2.1–2.2E–02	No
1900×	06	2249–2253–2311	M1.0–9.7E–03	Yes
1920+	07	0002–0024–0040	X5.4–6.7E–01	Yes
2070+	07	1619–1622–1626	C1.6–4.3E–04	No
2260×	08	1617–1623–1627	C1.1–6.7E–04	Yes
2310×	09	0322–0353–0418	M6.3–1.3E–01	Yes
2430×	10	0233–0239–0245	C3.5–1.9E–03	No
2480×	10	0731–0746–0801	C1.9–2.8E–03	Yes
2560×	10	1715–1744–1830	M8.4–2.6E–01	Yes
2810×	11	0321–0323–0326	C2.3–8.4E–04	No

^aSpace Weather Prediction Center (SWPC), see www.swpc.noaa.gov/. All reported X-ray events are from the GOES satellite data during excellent observing conditions.

^bThe sign (+) after the event number indicates that more than one report was given for this event.

^cWas the flare associated with a CME?

7.2. 相关事件案例研究

与该事件有关的研究论文有 40 篇。

7.2.1. 自动跟踪黑子群

Gyori (2015, Solar Phys, 290, 1627 - 1645) 基于集合与图形操作发展了一种在一系列连续太阳图像中发现和跟踪黑子群样体及其属性（位置、面积、磁场、强度等）的方法，用 SDO/HMI 数据对 NOAA11429 活动区进行了应用。在 X5.4 耀斑期间，在本影族的磁场族中发现了短暂的顺变及长久的变化，靠近极性翻转线(PIL)两侧相对的两个小本影族显示视场磁场的阶梯突变，正极性族减少，而负极性族增加，一些大型本影族在耀斑期间黑度也显示突然减少。作为被推向相反磁性半影区长、窄磁条的一部分，本影族可能是一些耀斑的触发原因，两个大的反极性本影族经历剪切与收缩运动，这些族运动曲线的破裂及转点与耀斑有关。

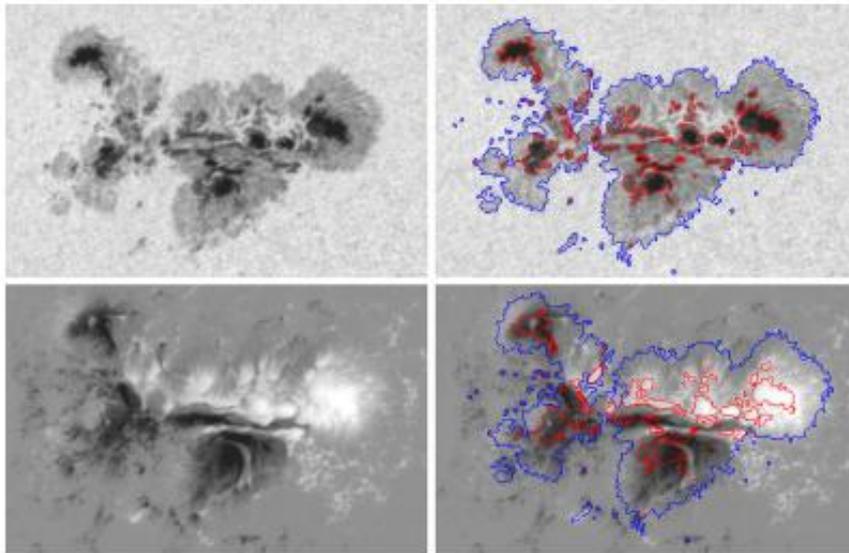


Figure 1 White-light images (top row) and magnetograms (bottom row) of NOAA AR 11429 taken on 2012 March 7 at 00:23:44 UT. The blue and red pixels in the images of the second column are boundary pixels of the penumbrae and the umbrae, respectively. Note that the spot boundaries determined for the intensity image are superimposed on the magnetogram. Penumbra and umbra boundaries are determined following Györi (1998).

图 7.7: NOAA 11429 活动区 (2012 年 3 月 7 日 00:23:44 UT) 在白光像 (上) 与磁图 (下) 上的黑子本影 (红线) 与半影 (蓝线)

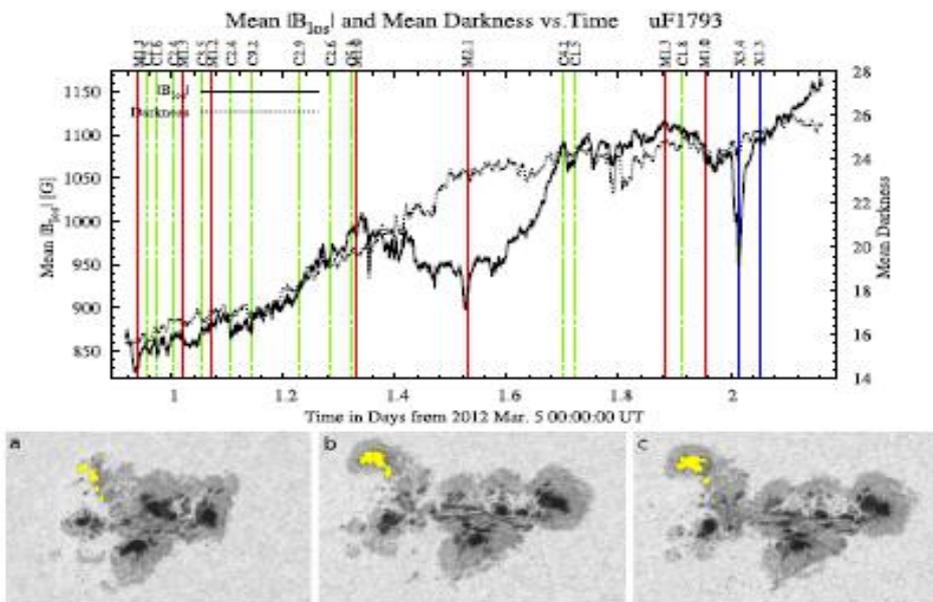


Figure 3 Upper panel: Time profile of the absolute value of the LOS mean magnetic flux density (solid curve) and the mean darkness (dotted curve) for the umbra family shown in the lower panels at different times (yellow). Note that darkness is by definition a dimensionless quantity, see its definition in Section 4.1. The color vertical lines show the times of the flares: dashed-dotted green, dashed red, and solid blue designate C, M, and X classes, respectively. (a) 2012 March 5 22:00:29 UT, (b) 2012 March 7 00:23:44 UT (X5.4 flare), and (c) 2012 March 7 03:58:59 UT.

图 7.8: 本影族 (下) 的平均磁通密度 (实线) 及黑度时间轮廓

7.2.2. NOAA 11429 活动区 M7.9 耀斑期间磁瞬变

Harker 和 Pevtsov (2013, APJ, 778, 175) 用 SDO/HMI 数据分析了 NOAA 11429 活动区 M7.9 耀斑期间的磁图、多普勒图、强度图、Stokes I 和 V 轮廓，在耀斑起始，负通量的瞬变快迅速出现在正极性的半影内，讨论了这是磁场结构真实的变化还是仪器影响，认为这是磁场的真实变化。

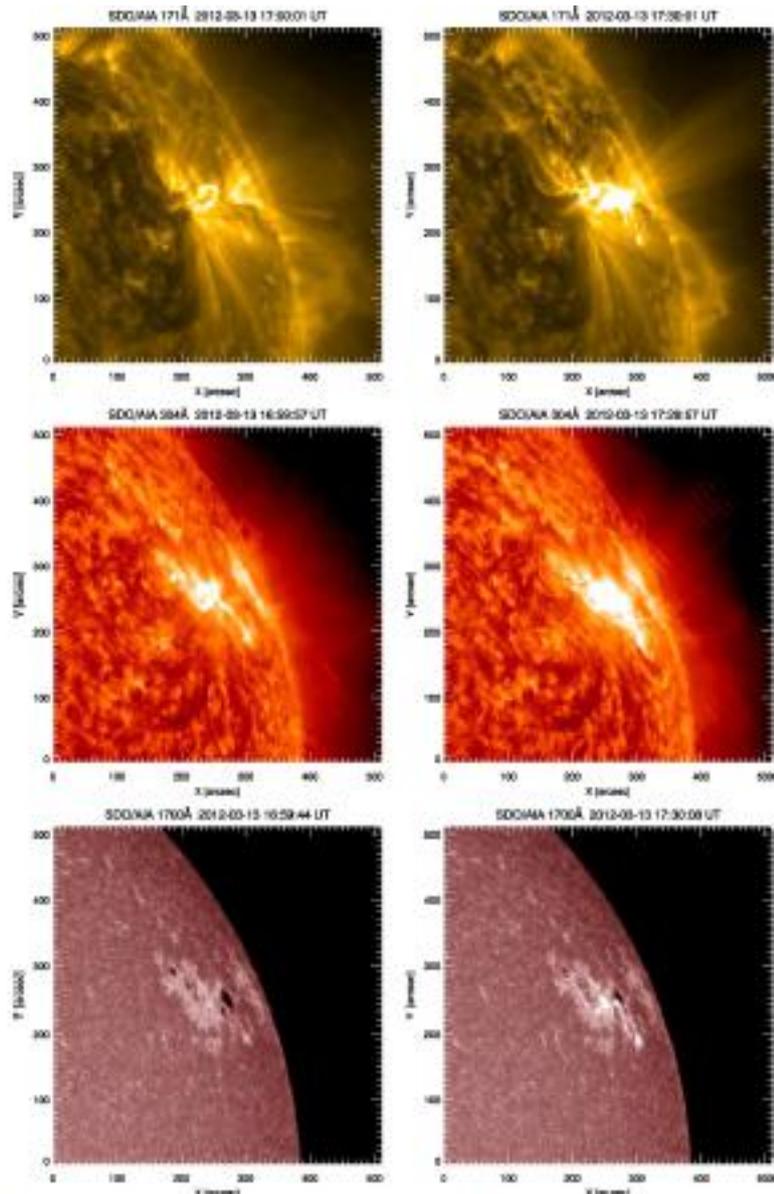


Figure 1. SDO/AIA images showing NOAA 11429 both before the flare (left) at 17:00 UT and during the flare (right) at 17:30 UT. The images depict coronal (top), chromospheric (middle), and photospheric (bottom) wavelengths. The flare is easily visible as enhanced brightness in all three atmospheric layers.

图 7. 9: NOAA 11429 耀斑前 (左) 及期间 (右) SDO/AIA 图

7.2.3. NOAA11429 活动区声晕的声学发射增强

Hanson (2015, Solar Phys, 290:2171 - 2187) 使用 SDO/HMI 数据, 利用高频 p 模谱的声学全息像分析了 NOAA11429 活动区声晕的声学发射增强, 发现在中等场强度区声源明显增强, 在活动区于晕之间识别出了一个转换区, 声源能量被中等场强的倾斜场阻碍了。

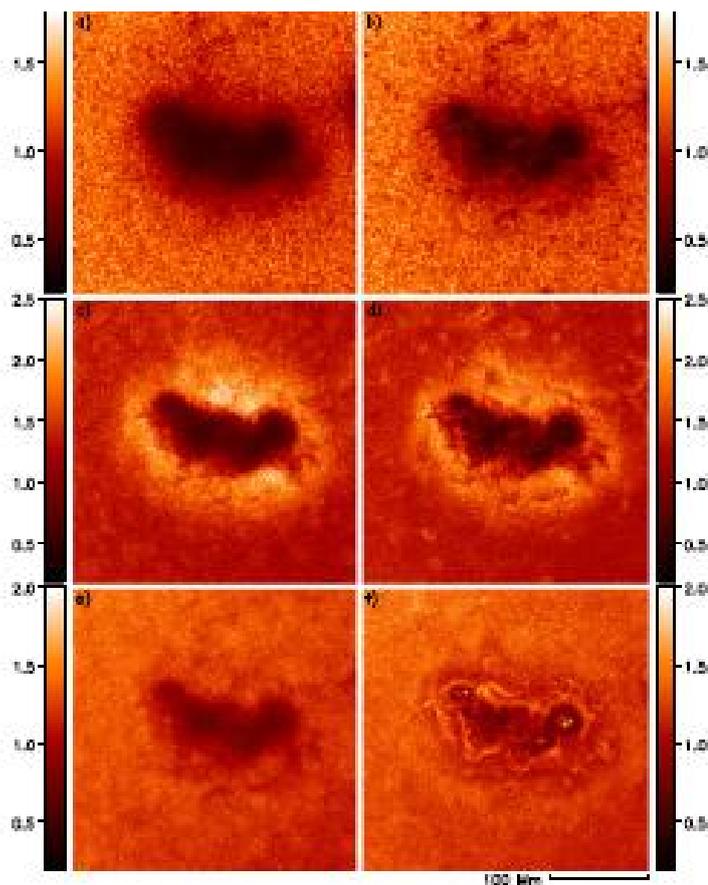


Figure 2. Acoustic-source (left) and local acoustic power (right) of AR 11429, averaged over 24 hours. From top to bottom the frequencies of the power maps (1 mHz band width) are centered at 3, 6, and 9 mHz. The maps are normalized to the quiet Sun.

图 7. 10: 11429 活动区在频率 3, 6, and 9 mHz 的声源 (左) 与声能 (右)

7.2.4. 一对大日冕物质抛射出现前限制耀斑期间磁绳的形成

NOAA 11429 活动区是一对超快 CME 的源, 两者相间不到一小时, 这个活动满足超级活动区的要求: 与 Hale 定律不兼容及, 其中一个与一个大磁暴

(Dst=-143nT) 相关，磁绳是缠绕结构，Chintzoglou 等 (2015, APJ, 809, 34) 使用 SDO 及 STEREO 数据，利用非线性无力场外推方法，发现了两个分离、弱缠绕磁绳系统，说明磁绳爆发前的存在最终形成两 CME 的种子。

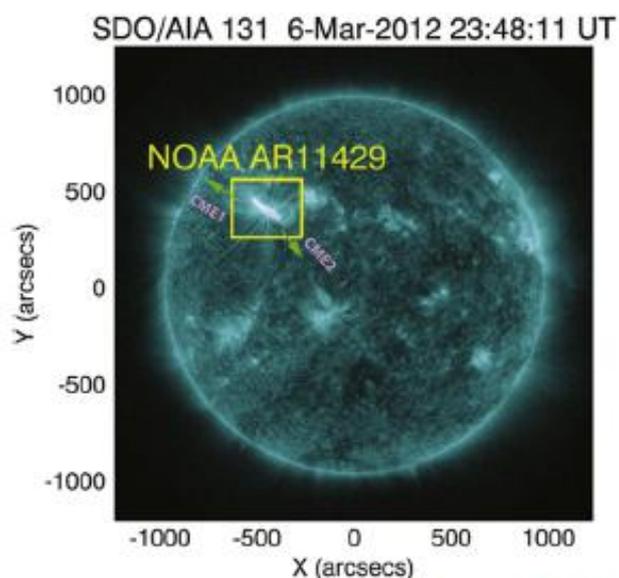


Figure 1. Full disk image from *SDO/AIA* at 131 Å identifying AR 11429. The size of the box is $500'' \times 400''$. The direction of the CMEs at the onset of the eruptions is shown with the green arrows.

图 7. 11: SDO/AIA 131 Å 图 (NOAA 11429 活动区) 及 CME 方向

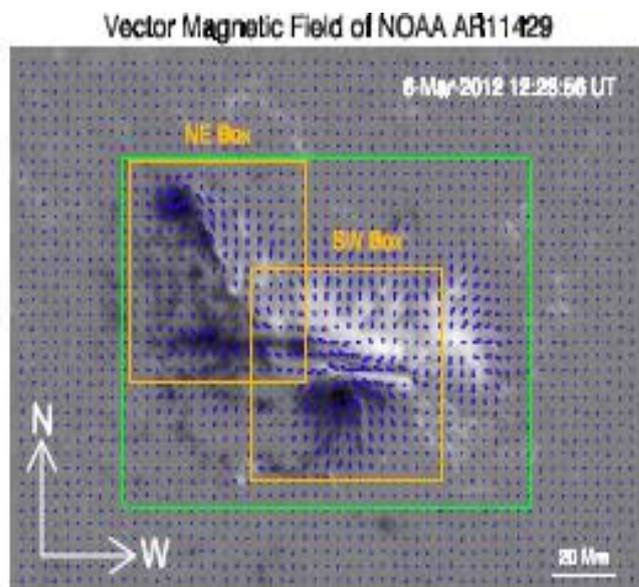


Figure 2. Sample CFA magnetic vector map from the HMIS/SDO taken at the time indicated. The grayscale image is the normal component of \vec{B}_{pot} situated at a 2500 G. The horizontal photospheric magnetic field, \vec{B}_h is shown with blue vectors. Note the alignment of the horizontal field along the PIL (observational manifestation of high PIL-shear). The two orange boxes shown enclose the NE and SW PIL, respectively (boxes show PCWs used in Figure 13). The green dotted window was used for the calculation of the magnetic flux (in Figure 3).

图 7. 12: NOAA 11429 活动区的两磁场区域

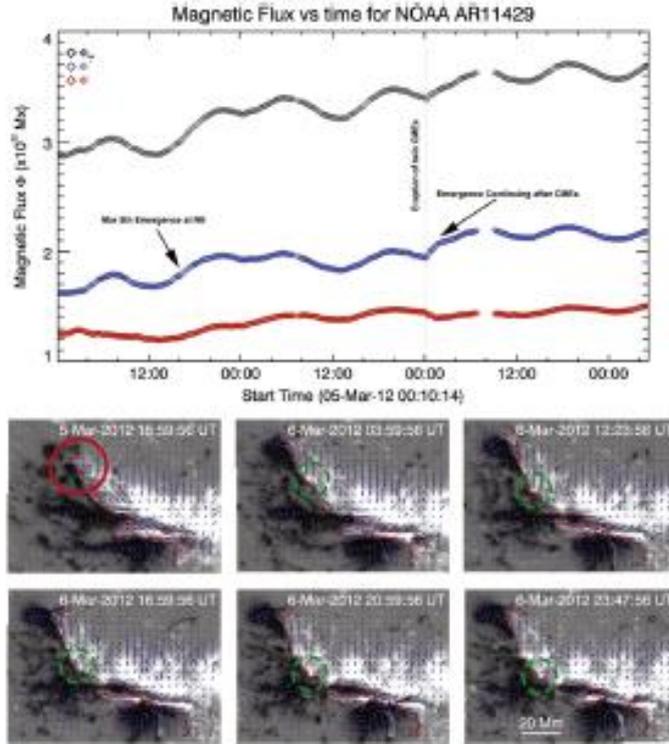


Figure 3. Top: the evolution of the magnetic flux for AR 11429 between 2012 March 5 and 6 (black diamonds: total unsigned, blue: positive, red: negative). The 1 day period oscillatory behavior is due to intrinsic instrumental problems of the HMI magnetograph becoming obvious in strong-field regions. Nevertheless, the overall trend is increasing in accordance with a continuously developing AR 11429. There are two distinctive flux emergence events showing their imprints in the flux profile—one on 2012 March 5 and a second one during/after the eruption of the twin CMEs (shown with arrows). Bottom panels: the time evolution of the photospheric vector field during 2012 March 5 and 6, i.e., before the eruptions of 2012 March 7. The blue vectors illustrate the horizontal component of the photospheric magnetic field. With red color we delineate the PIL (obtained by calculating the gradient of the A_z component). Note that, while the overall spatial distribution remains the same, significant changes occur along the PIL, by means of shearing motion of individual flux elements (green dashed circles, most notably in the NE side of the PIL—white “blobs,” following an emergence event on 2012 March 5 close to the NE negative polarity; location is shown with a red circle). Shearing occurs at the location of the SW negative sunspot with the elongated positive polarity on top of it.
(An animation of this figure is available.)

图 7. 13: NOAA 11429 活动区的磁通演化

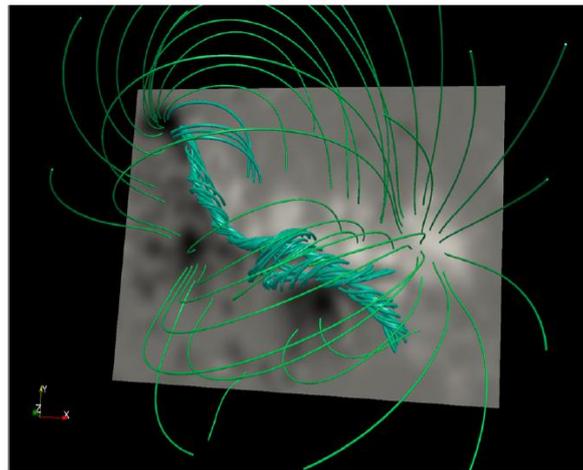


Figure 11. NLFFF extrapolation of 2012 March 6 23:48 UT. The grayscale map is the B_z component of the photospheric boundary at that time. The colored tubes represent the extrapolated magnetic field in the domain. The teal-colored tubes correspond to the field lines along the PIL. The magnetic field lines are highly sheared which indicates the existence of strong electric currents in the vicinity of the PIL. These field lines are rooted in randomly sampled points within areas of $|\alpha| = 5 \times 10^{-9} \text{ cm}^{-1}$ at the surface. Note the existence of two main “chains” of non-potential field lines—a short one, above the negative sunspot in the south and a longer one following the NE PIL. These correspond to the locations of the brightenings seen in 131 Å and also to the locations of initiation of the two CMEs. The green tubes represent the overlying (nearly potential) field lines sampled randomly in the FOV.
(An animation of this figure is available.)

图 7. 14: 非线性无力场外推

7.2.5. 两个连续耀斑爆发的磁场重构

Wang 等 (2014, APJ, 791, 84) 基于 SDO/HMI 矢量磁图, 通过非线性无力场外推方法分析了 NOAA11429 活动区两个连续耀斑爆发并研究了其磁重构, 在耀斑爆发期间磁自由能向下跳跃了 20-30%, 磁螺度注入率的符号改变可能与爆发有关, 磁场“爆炸”现象与第一个 X 耀斑的发生紧密相关。

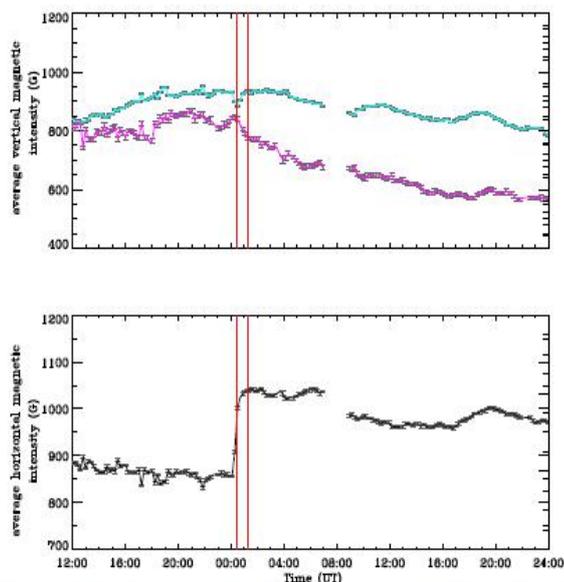


Figure 2. Average vertical magnetic intensity (upper panel) and horizontal field (bottom panel) near the neutral line as a function of time. The cyan and purple lines represent positive and negative field components in the upper panel. The thicker and thinner vertical red lines represent the first and second GOES flare peak times, respectively. The uncertainties of the average magnetic field are plotted as error bars in 3σ level.

图 7. 15: 中性线附近的垂直磁场 (上) 与水平场, 两红线为两耀斑时刻

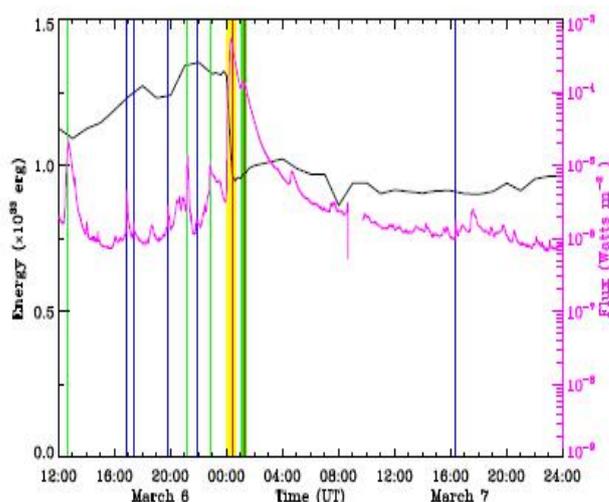


Figure 4. Evolution of the magnetic free energy of AR 11429 from 12:00 UT on March 6 to 23:48 UT on March 7. The solid black line corresponds to the magnetic free energy and the purple curve corresponds to the GOES soft-X ray flux (1–8 Å channel). Vertical blue, green, and red lines denote the peak times of C-, M-, and X-class flares, respectively, with their thickness roughly corresponding to the magnitude of the flare class. The vertical yellow and green squares in both panels correspond to the intervals of the first and second eruptions, respectively.

图 7. 16: 自由能的演化 (黑) 与 GOES 软 X 射线流量 (紫)

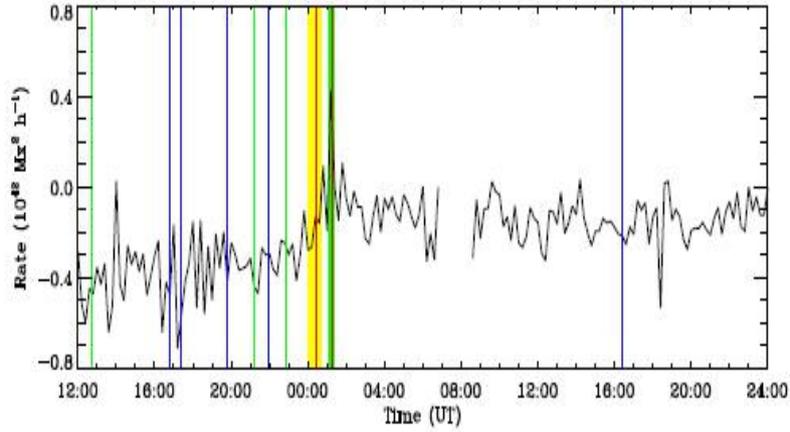


Figure 5. Helicity injection rate as a function of time, which is determined by Equation (5). The vertical lines and squares have the same meaning as in Figure 4.

图 7. 17: 磁螺度注入率

7.2.6. NOAA 11429 活动区的面积与倾角

Elmhamdi 等 (2013, *New Astronomy*, 23-24, 73 - 81) 利用沙特阿拉伯国王大学天文台 (AOKSU) 白光像研究了 NOAA 11429 活动区的黑子群面积与倾角, 面积显示三个相位, 面积与倾角紧密相关。

表 7. 3: 沙特阿拉伯国王大学天文台 (AOKSU) 白光像参数

Table 1 Main location & image characteristics.	
Observatory	
Location	KSU-Astronomical Observatory (Riyadh; Saudi Arabia)
Latitude	24 43' 15" North
Longitude	46 37' 4" East
Altitude	677 m (above sea level)
Full-disk Image	
Image Full-Frame Size	4284 × 2844 pixels
Used Exposure time	1/2500–1/3200 s
Estimated pixel scale (on Sun-disk)	~0.77 arcsec per pixel

表 7. 4: NOAA 11429 活动区参数

Table 2
NOAA AR 11429 properties & estimated parameters.

Date (JD + 2450000)	CM* Location Carrington System	Magnetic class	Area (in μHem) corrected for foreshortening	Tilt-angle ^c (deg)	Sidereal ang. vel. (deg.day^{-1})	X-ray flares ^d		
				X		M	C	
03/03 ^b	-	$\beta-\gamma$	-	-	-	0	0	3
04/03 (5990.915)	21.35-300.5	$\beta-\gamma-\delta$	848 ± 100	17.65 ± 3.5	-	0	1	3
05/03 (5991.904)	19.2-300.2	$\beta-\gamma-\delta$	1160 ± 150	13.47 ± 2.9	-	1	3	12
06/03 (5992.887)	20.2-300.8	$\beta-\gamma-\delta$	1319 ± 150	5.834 ± 1.6	14.719	0	6	5
07/03 (5993.892)	19.15-300.5	$\beta-\gamma-\delta$	1318 ± 150	5.096 ± 1.7	13.972	1	0	1
08/03 ^b	-	$\beta-\gamma-\delta$	-	7.615 ± 1.4	-	0	0	1
09/03 (5995.927)	18.15-299.75	$\beta-\gamma-\delta$	1184 ± 100	9.0558 ± 1.4	13.698	0	1	0
10/03 (5996.905)	18.1-299.8	$\beta-\gamma-\delta$	1185 ± 100	8.03 ± 1.5	14.230	0	1	2
11/03 (5997.884)	17.55-300.3	$\beta-\gamma-\delta$	984 ± 100	5.44 ± 1.6	14.662	0	0	1
12/03 (5998.879)	18.45-299.55	$\beta-\gamma-\delta$	788 ± 80	6.77 ± 1.9	13.408	0	0	1
13/03 (5999.893)	18.4-299.4	$\beta-\gamma$	706 ± 80	5.9 ± 2.5	14.044	0	1	1
14/03 (6000.882)	19.2-299.1	β	544 ± 80	-	13.837	0	0	0
15/03 (6001.927)	-	β	-	-	-	0	0	2

^a Center of mass of the sunspot-group region.
^b Not covered by our local observations.
^c Based uniquely on SDO/HMI magnetograms.
^d Daily number of each flare-class.

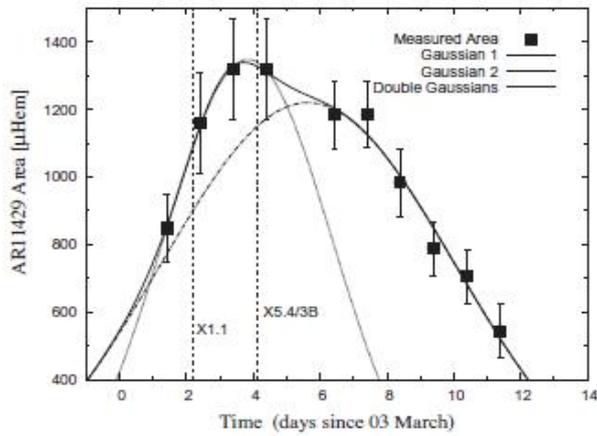


Fig. 5. NOAA AR 11429 area curve. The filled squares represent daily measurements of the group area corrected for foreshortening (as described in the text). The thick continuous line indicates the best double-Gaussian fit to the area curve (whole data points). The dotted line (labeled Gaussian 1) is the best fit considering only first 4 points, while shown in dot-dashed line (labeled Gaussian 2) is the best fit using the last 6 data. The time positions of the X1.1 and X5.4/3B intense flares are shown in dashed lines.

图 7. 18: NOAA 11429 活动区面积演化

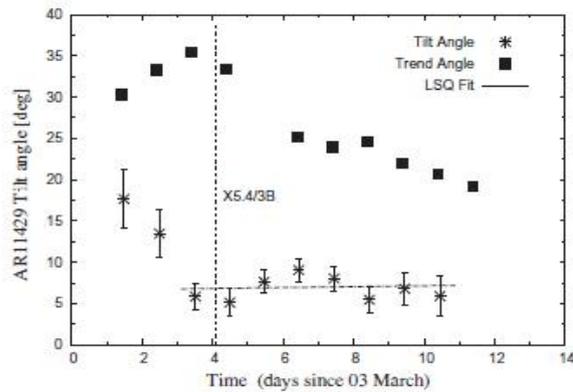


Fig. 7. Temporal evolution of the tilt & trend-angles as introduced in the text. The dotted vertical line refers to the time location of the major X-flare. The dot-dashed line indicates the weighted LSQ fit to the measured tilt-angles excluding the early two early measurements.

图 7. 19: NOAA 11429 活动区倾角演化

7.2.7. 像素动力分析法

Rasca 等 (2016, APJ, 832, 53) 提出了一种像素动力分析法, 发现光球吸收线谱的轮廓, 确定线移、宽度、非对称性及峰值的变化, Fe I 6301.5Å 谱的线宽与峰值变化与 NOAA 11429 的 M7.9X 耀斑存在明显的空间及时间关系。

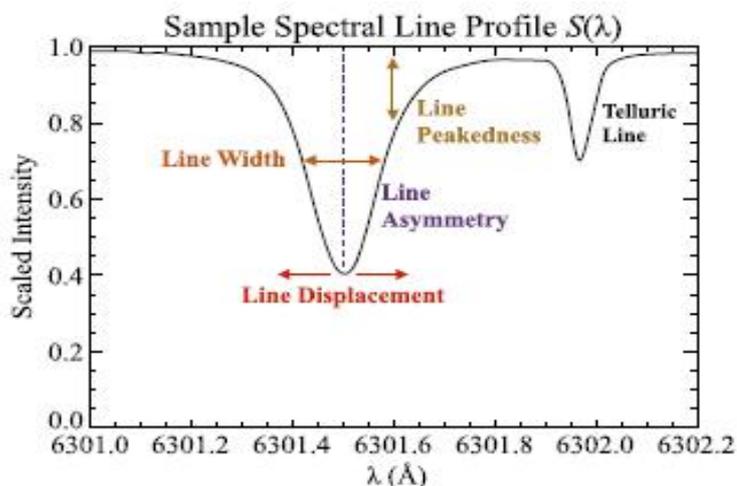


Figure 2. Smoothed Stokes I spectral line profile for a single pixel obtained by the SOLIS VSM instrument with a normal spectral sampling of $d\lambda = 23 \text{ m}\text{\AA}$. The wavelength range shows the Fe I 6301.5 Å absorption line (left), resolved by ~ 10 spectral points at full width at half maximum (FWHM), along with a telluric absorption line (right). The four absorption line properties discussed—line displacement, width, asymmetry, and peakedness—are indicated on Fe I 6301.5 Å.

图 7. 20: Stokes I 谱线平滑轮廓 (SOLIS VSM 仪器)

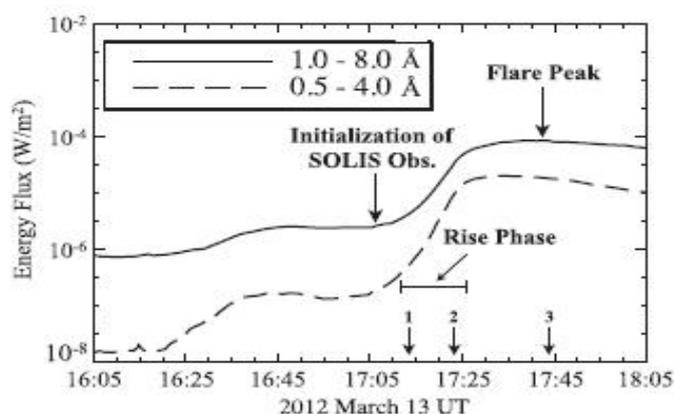


Figure 3. GOES X-ray flux profiles during the initiation of a large M-class X-ray flare at 17:12 UT on 2012 March 13. Both wavelength range profiles capture the initiation and rise phase leading to the flare peak. The initial SOLIS/VSM area scan is indicated around 17:06 UT ($m = 1$), which continue until 18:06 UT.

图 7. 21: GOES X 射线流量轮廓 (在打 M 级耀斑初始阶段)

7.2.8. 从太阳岛日球层顶 CME 的传播

Liu 等 (2014, APJL, 788:L28) 利用 STEREO A 和 B、Voyager 2 (V2) 和 V1、Wind 等数据分析了 NOAA 11429 活动区产生的一系列 CME 事件, 在地球附件观察到了一族激波事件及行星 CME 事件, 瞬变流相互作用抹去了源的记忆并与前导激波形成了一个混合相互作用区(MIR)。

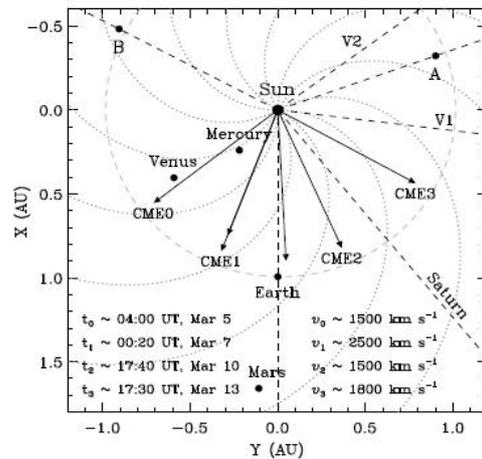


Figure 1. Positions of the spacecraft and planets in the ecliptic plane on 2012 March 10. The dashed lines indicate the longitudes of the Earth, STEREO A and B, V1 and V2, and Saturn, respectively. The gray dashed circle represents the orbit of the Earth, and the dotted lines show Parker spiral magnetic fields created with a solar wind speed of 450 km s⁻¹. The arrows mark the propagation directions of the major CMEs in 2012 March estimated from the longitudes of their source locations on the Sun. The estimated CME speeds and launch times on the Sun are also given.

图 7. 22: 地球、STEREO A 和 B、V1 和 V2、土星的位置

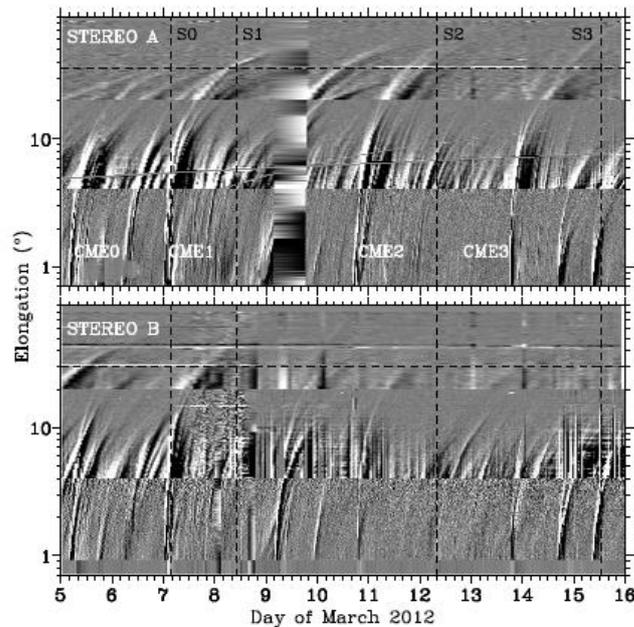


Figure 2. Time-elongation maps constructed from running-difference images of COR2, HI1, and HI2 along the ecliptic for STEREO A (upper) and B (lower). Tracks associated with the CMEs of interest are indicated. The vertical dashed lines mark the observed shock arrival times at the Earth, and the horizontal dashed line denotes the elongation angle of the Earth.

图 7. 23: 天距角-时间关系

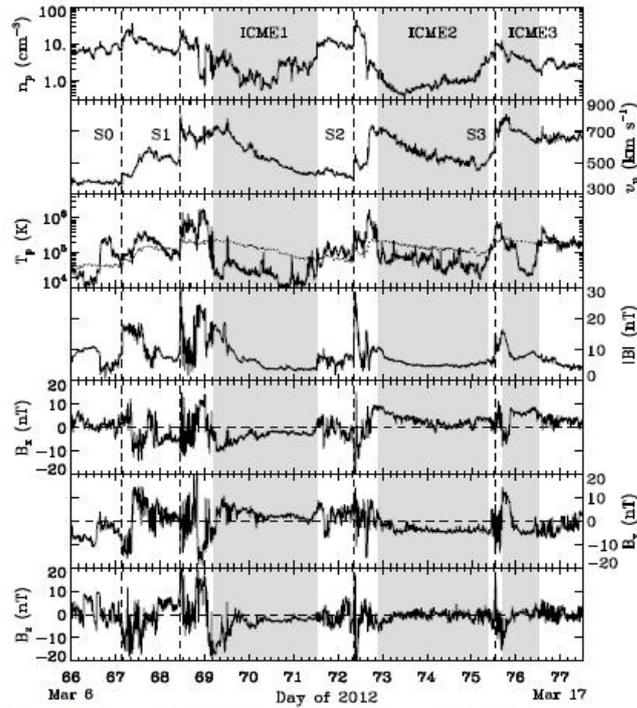


Figure 3. Solar wind plasma and magnetic field parameters observed at *Wind*. From top to bottom, the panels show the proton density, bulk speed, proton temperature, and magnetic field strength and components, respectively. The dotted curve in the third panel denotes the expected proton temperature from the observed speed. The shaded regions indicate the ICME intervals, and the vertical dashed lines mark the associated shocks.

图 7. 24: 太阳风与磁场参数

7.2.9. 黑子面积时间演化与相关等离子体流估计

Gafeira 等 (2014, *Solar Phys*, 289, 1531 - 1542) 使用 SDO 数据, 运用模糊集计算了几个活动区的黑子本影及半影面积、增长极衰退率, 一个经验的非旋转、均匀汇聚水平速度场与轴对称、随高度不变磁场的相关作用产生了黑子内非常复杂的对流特征。

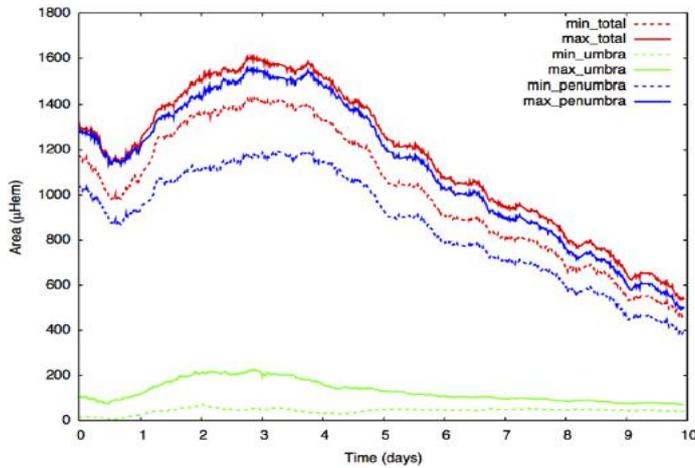


Figure 3 Area evolution of NOAA AR 11429: lowest (dashed lines) and highest (solid lines) fuzzy-area estimates for the total sunspot area (red lines), the umbra (green lines), and the penumbra (blue lines).

图 7. 25: NOAA 11429 活动区的面积演化

7.2.10.大耀斑期间光球磁场与洛伦兹力矢量的突然变化

Petrie (2012, APJ, 759, 50) 分析了 SDO 观测到的六个大耀斑期间光球磁和洛伦兹力的空间及时间变化, 中性线场矢量变得更强、更水平, 这几乎是水平场分量与中性线平行性的增强结果; 耀斑前中性线场比势场线更垂直、突然塌缩、更接近势场倾角, 说明与非势场倾角相关的磁张力松弛在大耀斑期间起了重要作用, 而剪切角并没有显示这种形状, 水平场变得更加显著且与中性线更对齐; 在耀斑期间, 洛伦兹力有一个大的、突然永久的向下变化; 水平洛伦兹力的行为变化在两侧以相反的方向更平行于中性线, 把中性线两侧拉得更靠近。

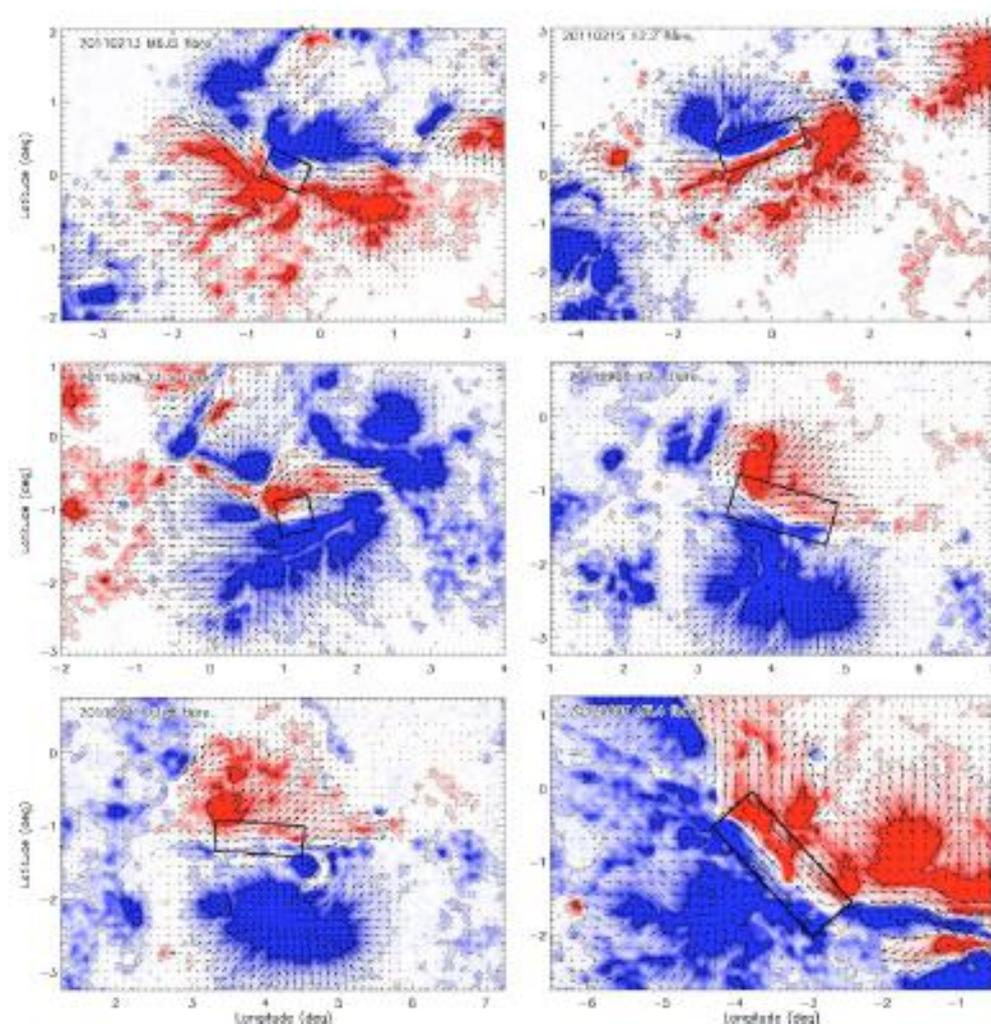


Figure 1. Vector magnetic field before each of the six flares. The vertical field component, B_v , is indicated by the color scale and the horizontal component by the arrows, with saturation values ± 1000 G. Red/blue coloring represents positive/negative vertical field. The black rectangles mark the regions of major field change near the neutral lines that are used in subsequent analysis. The solid and dotted contours indicate strong ($|B_v| > 1000$ G) and quite strong ($|B_v| > 100$ G) fields, respectively.

图 7. 26:六个耀斑前的矢量磁场

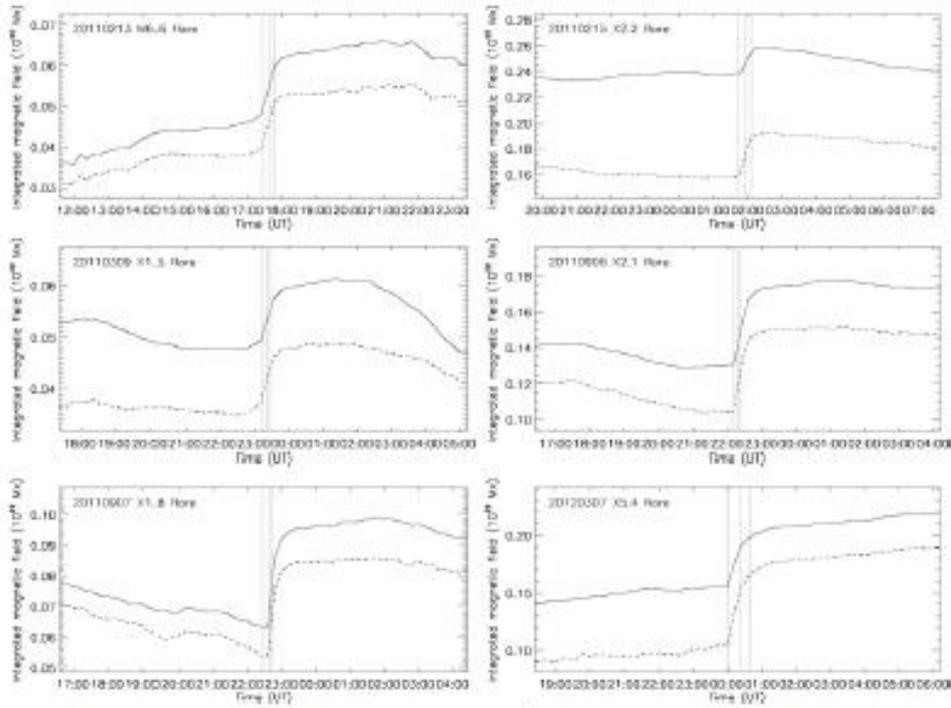


Figure 3. Shown here are the integrated magnetic field strength M^{2n} (solid lines) and B^{2n} (dashed lines) near each neutral line plotted against time. The areas of integration are indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.

图 7. 27: 中性线附近磁场强度积分的变化

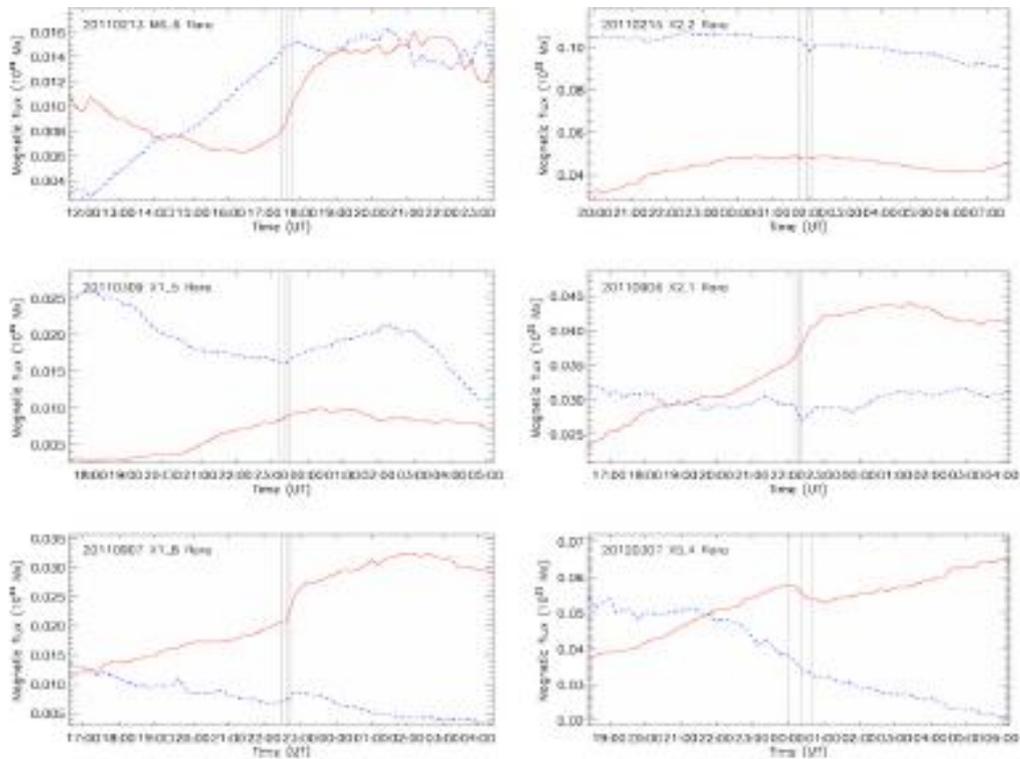


Figure 4. Shown here are the total vertical magnetic flux B^{2n} near each neutral line plotted against time. The red/blue solid/dashed lines represent positive/negative flux. The areas of integration are indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.

(A color version of this figure is available in the online journal.)

图 7. 28: 中性线附近总垂直磁场强度的变化

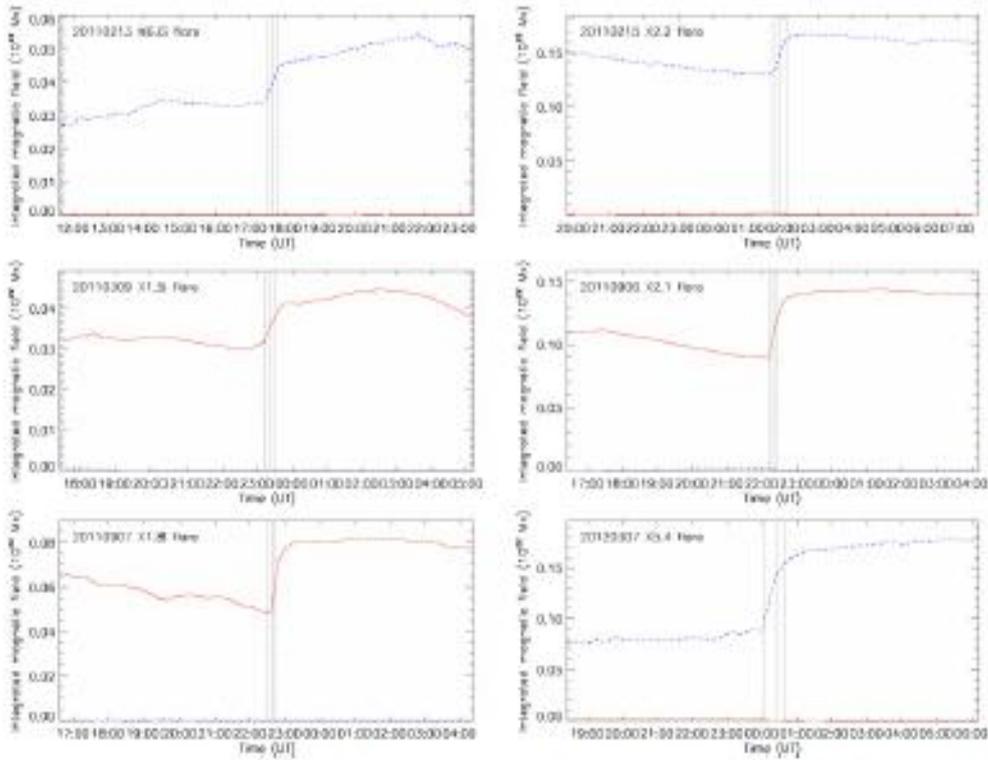


Figure 5. Shown here are the integrated horizontal field parallel to each neutral line, $A_{||}^{int}$, near each neutral line plotted against time. The red/blue solid/dashed lines represent positive/negative field, i.e., approximately westward/eastward field. The areas of integration are indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.
(A color version of this figure is available in the online journal.)

图 7. 29: 中性线附近总水平磁场强度的变化

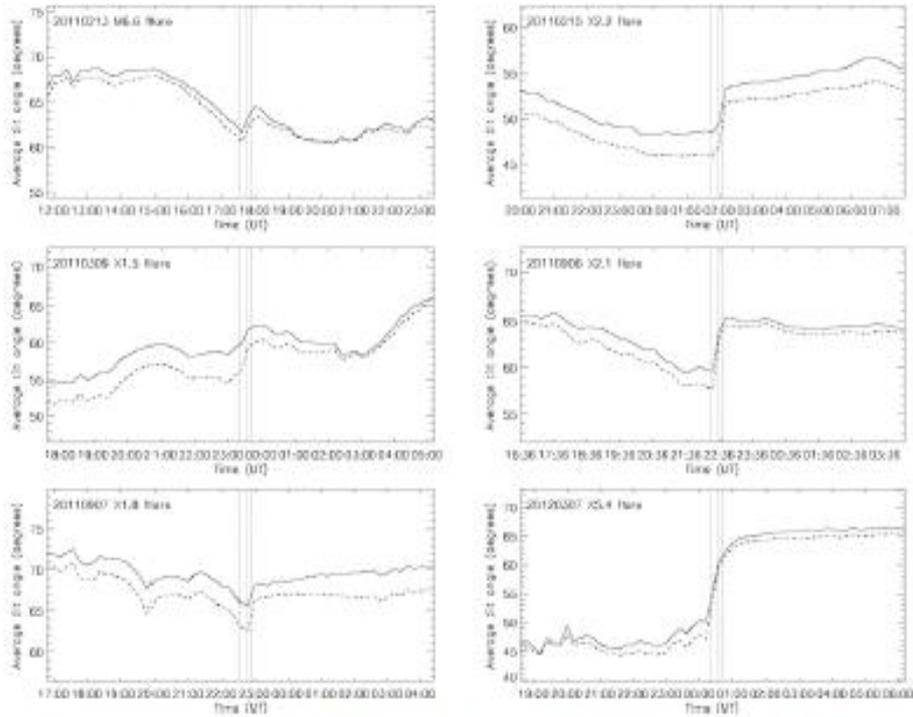


Figure 7. Shown here are the average tilt angles (solid lines) and the field-weighted average tilt angles (dashed lines) near each neutral line plotted against time. These angles are averaged over the areas of integration indicated by the black rectangles in Figure 1. The vertical lines represent the GOES flare start, peak, and end times.

图 7. 30: 平均倾角的变化

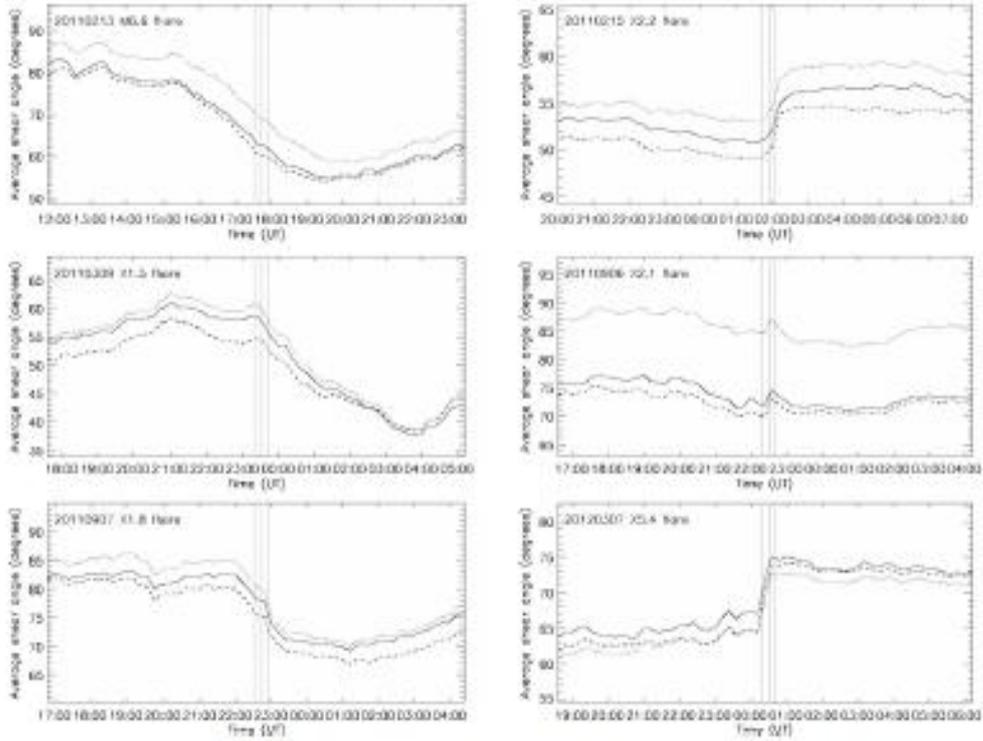


Figure 9. Shown here are the average shear angle (solid lines) and the field-weighted average shear angles (dashed lines) near each neutral line plotted against time. The average of the magnetic shear is also plotted (dotted lines) in units of G° , divided by 1.5×10^8 for the 2011 February 15 and March 9 flares and 10^7 for the other flares. These quantities are averaged over the areas of integration indicated by the black rectangles in Figure 1. The vertical lines represent the GONG flare start, peak, and end times.

图 7. 31: 平均剪切角的变化

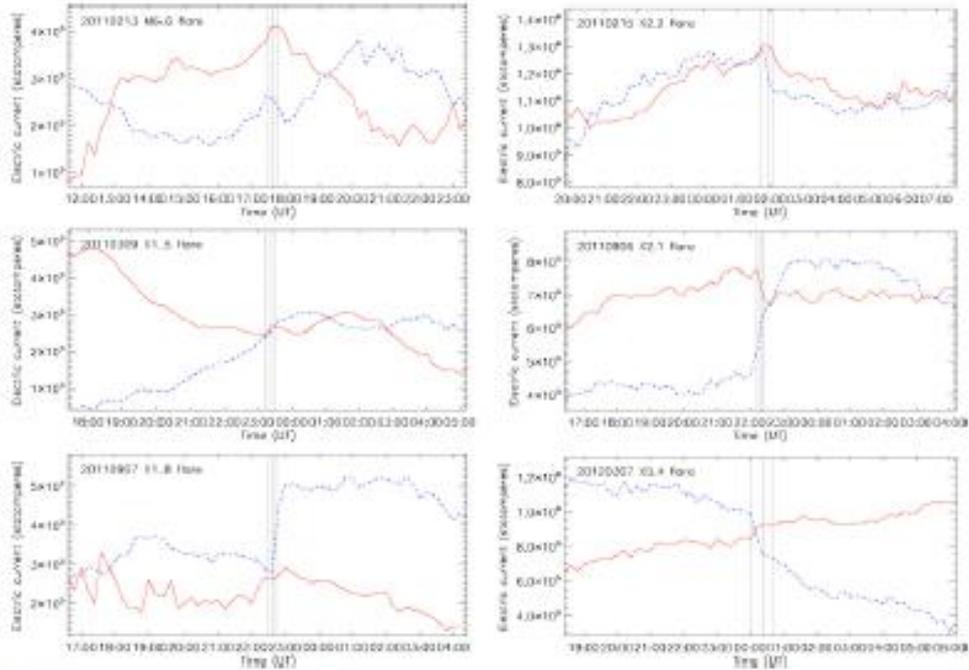


Figure 12. Integrated vertical electric current flux near each neutral line, J_z^{int} , is plotted here for each flare as a function of time. The red/blue solid/dashed lines represent positive/negative current. The vertical lines represent the GONG flare start, peak, and end times. The areas of integration for the neutral-line calculations are indicated by the black rectangles in Figure 1.

图 7. 32: 垂直电流通量的变化

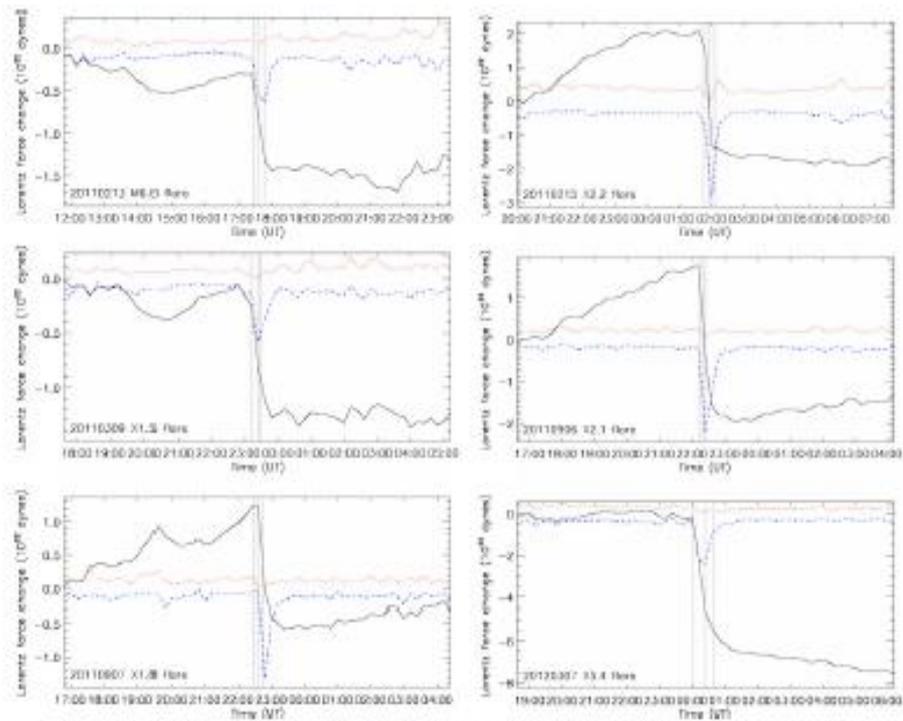


Figure 14. Lorentz force vector components in the vertical direction, $\Delta F_z^{(2)}$, are plotted as functions of time. The positive and negative running-difference changes are represented by the red dotted and blue dashed lines, respectively. The first-difference changes with respect to the first image are represented by the solid black lines. The areas of integration are indicated by the black rectangles in Figure 5. The red/blue dotted/dashed lines represent positive/negative force changes. The vertical lines represent the GONG flare start, peak, and end times.

图 7.33: 垂直洛伦兹力的变化

7.2.11.对地效应

2012年3月7-11日地球空间经历了大量的高强度空间天气现象，包括地24太阳活动周的第二大磁暴，观测到超低频波增强、辐射带相对论电子逃逸、及强能量电子注入，这些现象最终与两个超快CME(>2000 km/s)和两个X级耀斑相连。Patsourakos等(2016, APJ, 817, 14)使用一系列从太阳、日球层及地磁层的卫星数据，发现只有第二个CME指向地球，分析了到的地球的ICME磁场等性质。

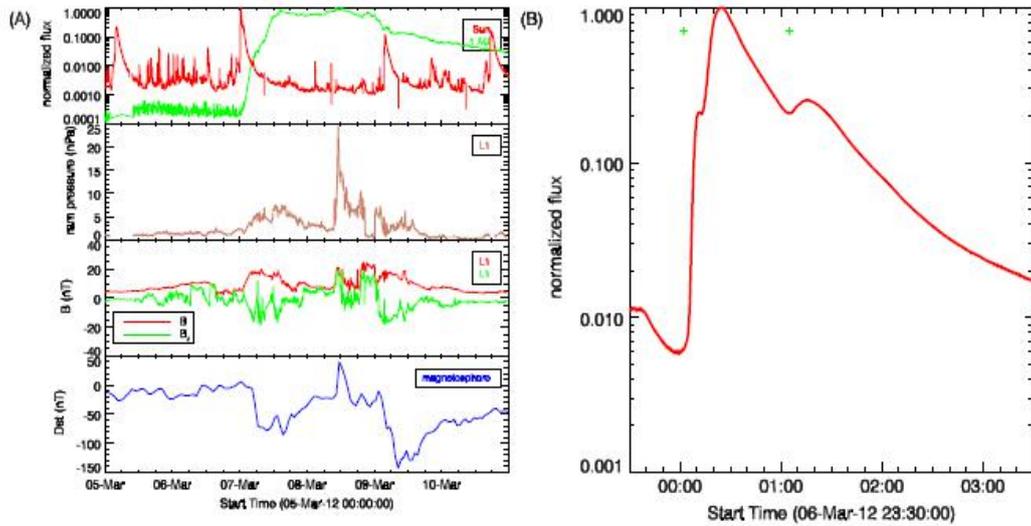


Figure 1. Panel (A): selected observations along the Sun–Earth line during the interval 2012 March 5–11. From top to bottom: GOES 1–8 Å SXR (red) and energetic protons with energies >30 MeV (green), solar-wind ram pressure at L1, magnetic field magnitude (red) and B_z (in the geocentric solar ecliptic (GSE) system, green) at L1, Dst index. Panel (B): GOES 1–8 Å SXR during the two reported X-class flares. The green crosses correspond to the onsets of the two X-class flares.

图 7. 34: (A) GOES 流量(red)与高能质子 (>30 MeV, green), 太阳风冲压 (ram pressure), 磁场强度, Dst 指数。(B): GOES X 射线流量

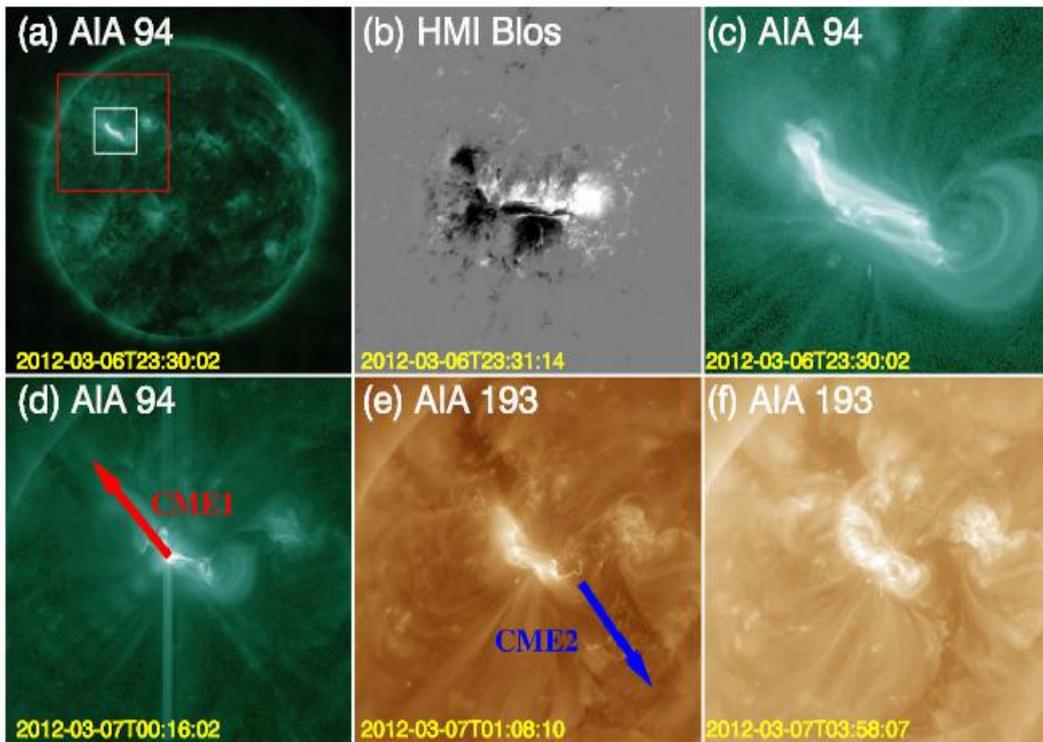


Figure 3. A description of the low-coronal configuration during the two eruptive X-class flares in NOAA AR 11429: (a) AIA 94 Å full-disk image less than an hour before the flares of 2012 March 7. The white box contains the source AR and is magnified in (b) and (c), while the red box contains a more extended field of view and is magnified in (d)–(f). The white and red boxes occupy areas of 300×300 arcsec² and 780×780 arcsec², respectively. The white box includes a photospheric line-of-sight HMI magnetogram (b) and the respective AIA 94 Å image (c). The red box includes a 94 Å AIA image obtained during the first flare (d), a 193 Å AIA image obtained during the second flare (e), and a 193 Å AIA image of the postflare phase (f). The inferred directions of the two corresponding CMEs in the inner corona, labeled here CME1 and CME2, respectively, are given by the red and blue arrows in (d) and (e), respectively.

图 7. 35: NOAA 11429 X 耀斑爆发 (2012,3,7) 前不到一小时 AIA 94 Å 图

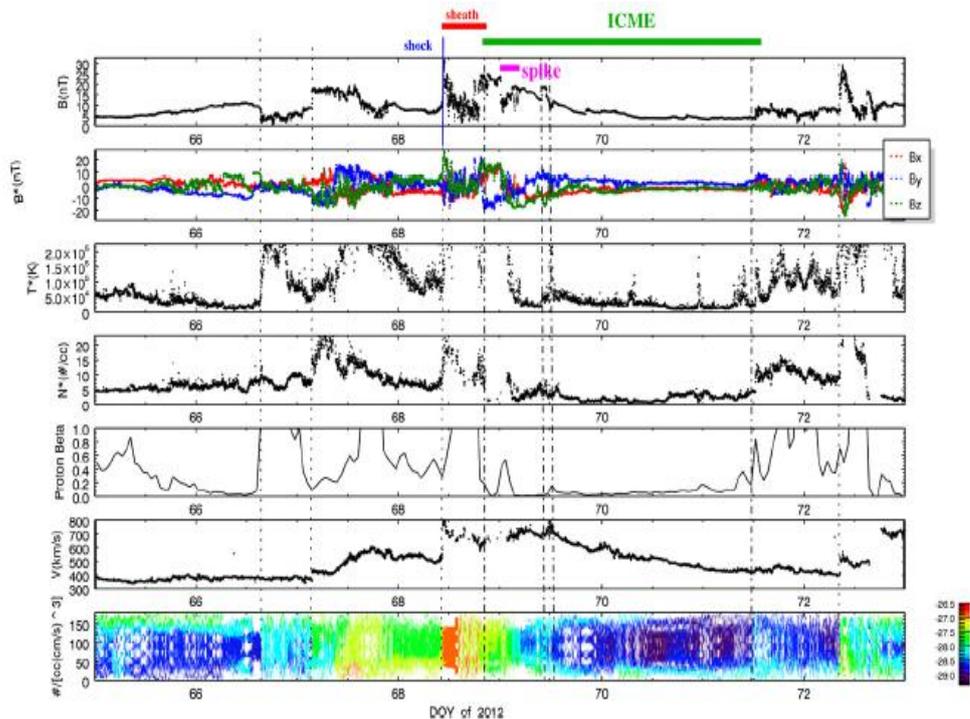


Figure 9. Wind L1 in situ observations (from top to bottom): magnetic field magnitude, magnetic field components in the GSE system; proton temperature; proton density; proton plasma β ; solar wind bulk velocity; pitch-angle distribution of energetic electrons at various energy levels. The vertical blue line marks the shock arrival, the red horizontal bar the associated sheath region, the green horizontal bar the ICME structure, and the magenta horizontal bar the magnetic field spike (all in top plot).

图 7. 36: Wind L1 观测

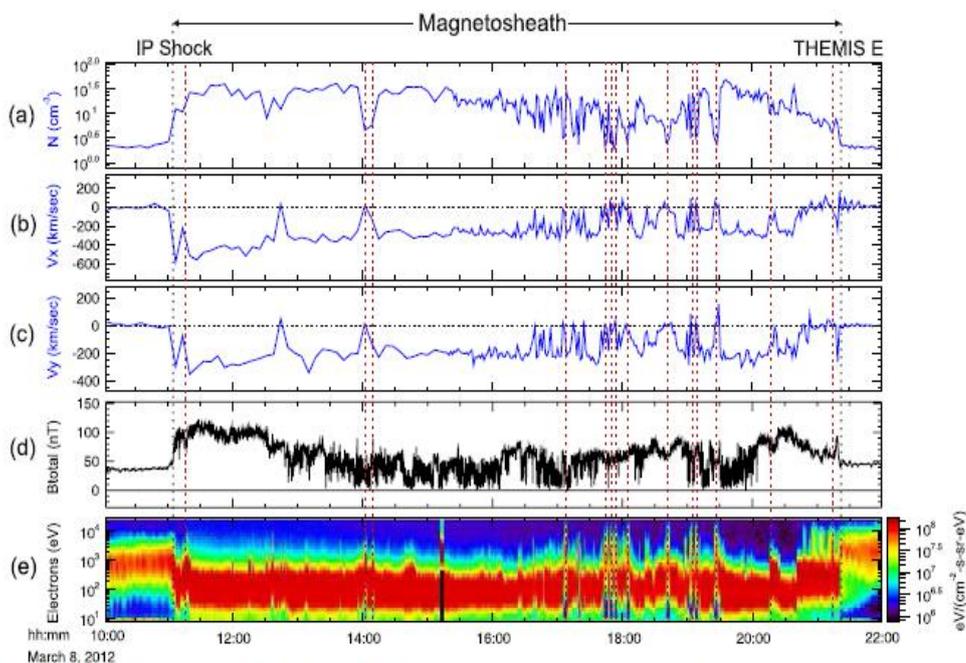


Figure 11. THEMIS E observations during 2012 March 8. Plots from top to bottom contain time-series of: (a) plasma density measured from the Electro-Static Analyzer (ESA; McFadden et al. 2008) instrument, (b), (c) the x and y components of the plasma flow velocity in geocentric solar magnetospheric (GSM) coordinates measured also from the ESA instrument, (d) the magnetic field strength B_{total} measured from the FGM (Flux/Gate Magnetometer; Auster et al. 2008) instrument, and (e) ESA electron plasma distribution. The vertical red dashed lines denote clear magnetopause crossings due to the oscillatory motion of the magnetopause, while the black dashed lines mark THEMIS E's initial entry to and final exit from the magnetosheath. Similar observational features were also registered from THEMIS A and D (not shown here).

图 7. 37: THEMIS E 观测 (2012 年 3 月 8 日)

7.2.12. 两个大 CME 事件前的分光谱特征

Syntelis 等 (2016, A&A, 588, A16) 使用 Hinode/EIS 和 SDO/AIA 数据, 利用微分发射量(DEM)识别出了通量绳及主活动区的发射分量, 跟踪了前者的时间演化, 对 NOAA 11429 活动区两个快速 CME 爆发前的形状进行了分光谱分析。第一个 CME 出现 5 小时前, 东侧区域的时间演化显示平均 DEM 增加了一个量级, 这与蓝移和非热速度增加显示的通量绳的逐步上升及加热有关, 观测到通量绳的整体向上运动。

表 7. 5: NOAA 11429 活动区的 X 及 M 级耀斑

Table 2. Summary of the M and X flares occurring in the AR.

Flare	Time (UT)	Region
M 2.1	March 6, 12:38	east
M 1.3	March 6, 21:11	west
X 5.4	March 7, 00:34	east
X 1.3	March 7, 01:05	west

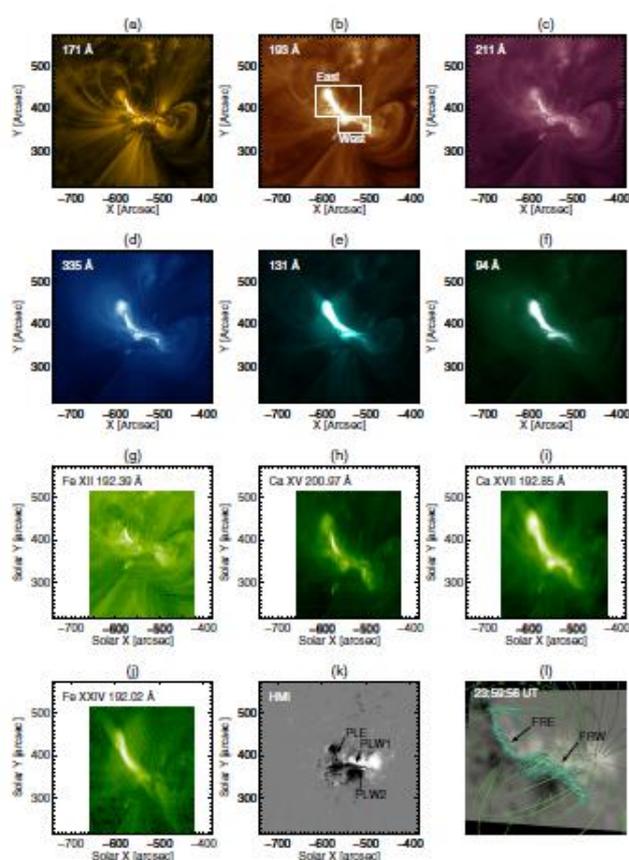


Fig. 2. Cutouts of AIA images of the AR at March 6, 12:55 UT shown in a) 171 Å; b) 193 Å; c) 211 Å; d) 335 Å; e) 131 Å; f) 94 Å. The white boxes in b) define two sub-regions named east and west. g) EIS intensity image during the 12:47–12:56 UT raster of Fe XII 192.39 Å, h) Ca XV 200.97 Å, i) Ca XVII 192.85 Å and j) Fe XXIV 192.02 Å. Panel sizes in EIS are the same as AIA for better comparison. White spaces in panels g)–j) are due to the smaller EIS FoV (see Fig. 1). k) HMI line of sight magnetogram. Arrows indicate three PILs, one in the east region (PLE) and two in the west region (PLW1, PLW2). l) Magnetic field extrapolation at March 6, 23:59 UT showing two flux rope structures, one in the east region (FPE) and one in the west region (FRW), surrounded by an envelope field. This figure is courtesy of G. Chintzoglou (see Chintzoglou et al. 2015).

图 7. 38: 不同谱线对 NOAA 11429 活动区的观测

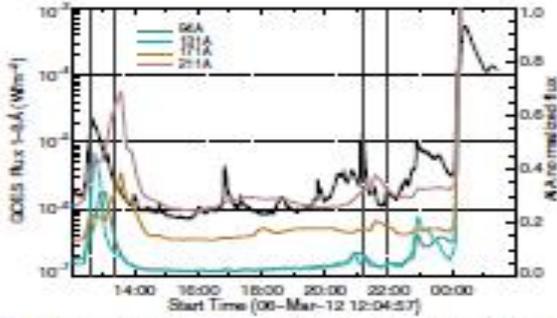


Fig. 3. GOES 1–8 Å flux from March 6, 12:05 UT to March 7, 01:25 UT. Vertical grey lines indicate the two time periods when Hinode/EIS performed rasters. The coloured lines are the 171 Å, 211 Å, 131 Å, and 94 Å AIA lightcurves taken over the whole AR cutout (white box, Fig 1).

图 7. 39: GOES 流量（黑）与不同谱线光变曲线

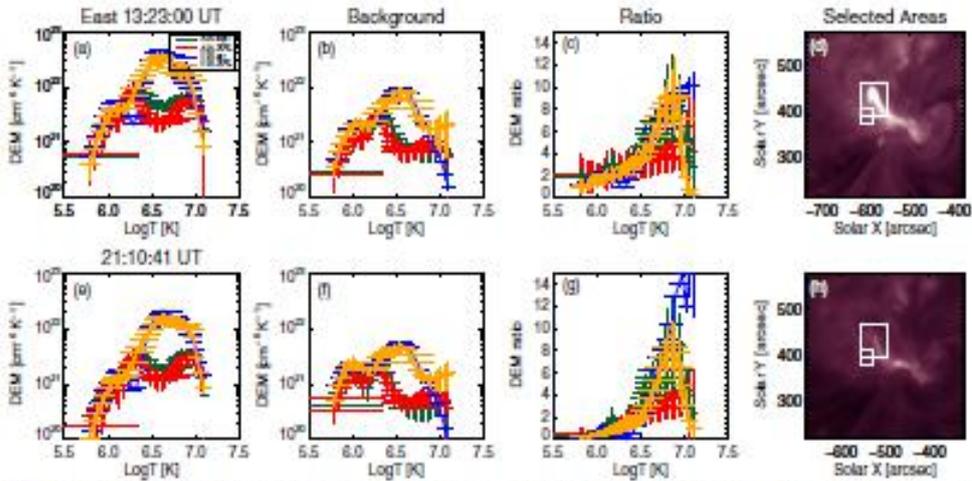


Fig. 5. EIS and AIA DEMs calculated at two different times. First row is from the 13:23–13:31 UT EIS raster. Second row is from the 21:10–21:19 UT raster. The intensities used for the DEMs are average values in the east region (big box in panels d) and h)) and in the background (small box in panels d) and h)). a), e) east region DEM for EIS (blue, orange) and AIA (green, red). b), f) Background DEM for EIS and AIA. c), g) east/background ratio. The blue and green lines use the Poisson noise as intensity error for the DEM calculation. The orange and red lines use 20% of the intensity value as intensity error. d), h) AIA 211 Å image showing the selected AR and background regions.

图 7. 40: 由 EIS 和 AIA 计算的 DEM

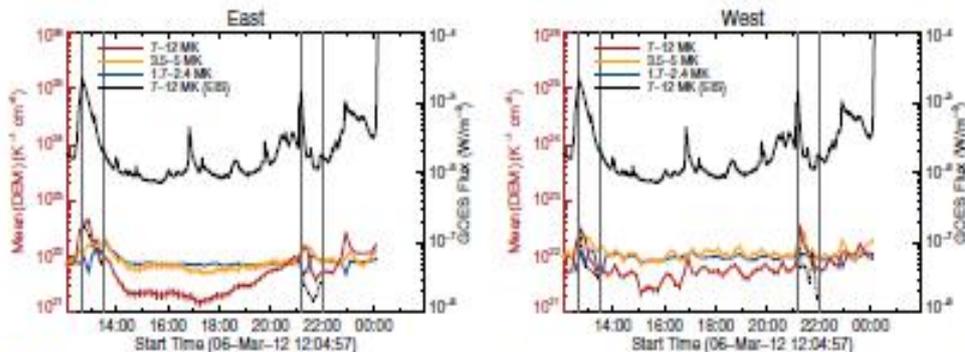


Fig. 7. AIA mean DEM timeseries in three temperature ranges 1.7–2.4 MK (solid blue), 3.5–5 MK (solid orange) and 7–12 MK (solid red) for the a) east and b) west regions. Black dashed lines indicate the mean DEM from EIS data in the 7–12 MK temperature range. The black solid lines show the GOES flux in the 1–8 Å channel. The vertical lines show the two time periods of the EIS rasters.

图 7. 41: 三个温度范围的 DEM

7.2.13. 超级活动区 11429 磁绳的 wist 和 Writhe

Elmhamdi 等 (2014, Solar Phys, 289, 2957 - 2970) 利用 SDO/HMI 数据分析 NOAA 11429 活动区的磁螺度、磁通、螺度积累、倾角的演化, 磁螺度通量与倾角似乎是时间相关的, 当倾角减少而负磁螺度积累时, 在第一观测阶段, 耀斑/CME 事件活动较高,

表 7. 6: NOAA 11429 活动区综述

Table 1 NOAA AR 11429 activity report^a - 6 to 11 March 2012.

Event ^b [SWPC Number]	Date (March 2012)	Begin-Max-End [UT]	Particulars (Class-Flux Peak [W m^{-2}])	CME ^c ?
1530 +	06	0022-0028-0031	M1.3-3.7E-03	No
1570 +	06	0136-0144-0150	M1.2-5.9E-03	No
1590 +	06	0226-0233-0237	C2.4-1.1E-03	No
1600 +	06	0324-0328-0331	C9.2-2.2E-03	No
1630 ×	06	0401-0405-0408	M1.0-2.6E-03	Yes
1650 +	06	0519-0528-0531	C2.9-1.4E-03	No
1690 +	06	0731-0743-0747	C5.3-3.2E-03	No
1700 ×	06	0752-0755-0800	M1.0-2.7E-03	Yes
1750 +	06	1110-1117-1122	C2.8-1.5E-03	No
1760 +	06	1223-1241-1254	M2.1-2.2E-02	No
1900 ×	06	2249-2253-2311	M1.0-9.7E-03	Yes
1920 +	07	0002-0024-0040	X5.4-6.7E-01	Yes
2070 +	07	1619-1622-1626	C1.6-4.3E-04	No
2260 ×	08	1617-1623-1627	C1.1-6.7E-04	Yes
2310 ×	09	0322-0353-0418	M6.3-1.3E-01	Yes
2430 ×	10	0233-0239-0245	C3.5-1.9E-03	No
2480 ×	10	0731-0746-0801	C1.9-2.8E-03	Yes
2560 ×	10	1715-1744-1830	M8.4-2.6E-01	Yes
2810 ×	11	0321-0323-0326	C2.3-8.4E-04	No

^aSpace Weather Prediction Center (SWPC), see www.swpc.noaa.gov/. All reported X-ray events are from the GOES satellite data during excellent observing conditions.

^bThe sign (+) after the event number indicates that more than one report was given for this event.

^cWas the flare associated with a CME?

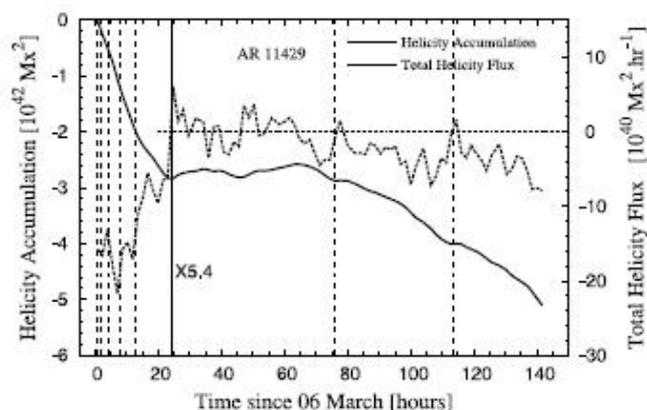


Figure 4 Temporal profile of magnetic-helicity accumulation in AR 11429 (continuous line). The thick dotted curve refers to the total helicity flux. Dashed vertical lines mark the M-class flares occurrence, while the dotted horizontal line shows the zero-value level in the total helicity flux. The strong GOES X5.4-class flare, maximum on 7 March 2012 00:24, is highlighted. Time $t = 0$ hours corresponds to 6 March 00:00.

图 7. 42: 磁螺度积累演化

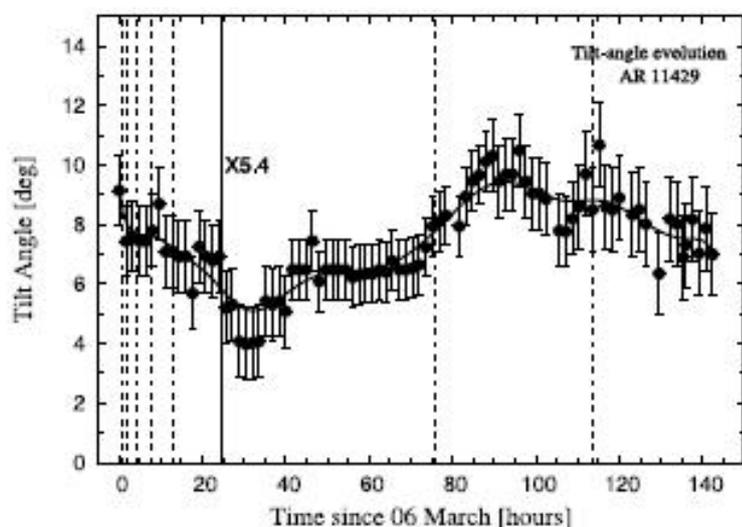


Figure 5 Tilt-angle evolution during the six-day period of interest. The line approximates the data with a Bézier Smoothing-curve of degree n (the number of data points) that connects the endpoints. Dotted vertical lines refer to M-class Flares. The X5.4-class flare is highlighted. Time $t = 0$ is taken to be at 6 March 00:00.

图 7.43: 倾角演化

7.2.14. 2012 年 3 月 5 日三个 CME 之间的相互作用

Colaninno 等 (2015, APJ, 815, 70) 使用 SOHO、STEREO-A 和 STEREO-B 数据, 运用向前拟合方法分析了发生在 2012 年 3 月 5 日三个 CME 之间的相互作用及运动行为, 当第二个 CME (CME-2) 在 02:45UT 从东边缘出现时第一个 CME (CME-1) 已经在继续, 这两个 CME 没有相互作用, 直到第三个 CME (CME-3) 在 03:34 UT 从 NOAA11429 活动区爆发, 速度为 $1456[\pm 31]$ km/s 的 CME-3 驱动了以激波, CME-3 驱动的激波通过 CME-1 时没引起后者在几何、轨迹及速度的改变, 然而, 当 CME-1 到达地球时在原地探测到的温度升高显示 CME-1 内的等离子体可能被激波的通过加热了, CME-2 被 CME-3 加速了两次以上, 在 CME-3 之前保持了独立的结构, CME-2 的 40 度偏角中有 24 度是由 CME-3 引起, 说明 CME-2 和 CME-3 的碰撞时超弹性的。

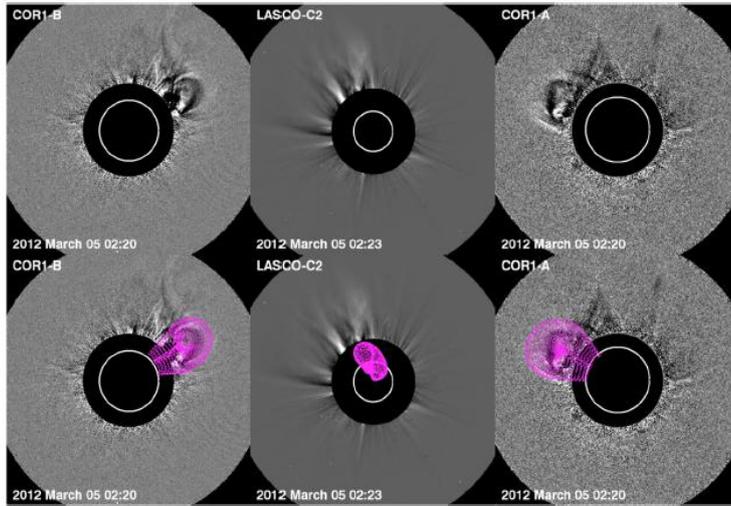


Figure 1. Contemporaneous observations of CME-1 from COR1-B (left), LASCO C2 (center), and COR1-A (right) and the GCS fit (magenta) overplotted for each viewpoint. CME-1 reached a height of $3.5 R_{\odot}$ before CME-2 is observed in the coronagraphs. We are able to continuously fit the observation of CME-1 with the GCS model, from its first emergence in COR1 until it leaves the COR2 FOV. (An animation of this figure is available.)

图 7. 44: 当观测到 CME-2 时, CME-1 已经上升到 3.5Rsun 高度

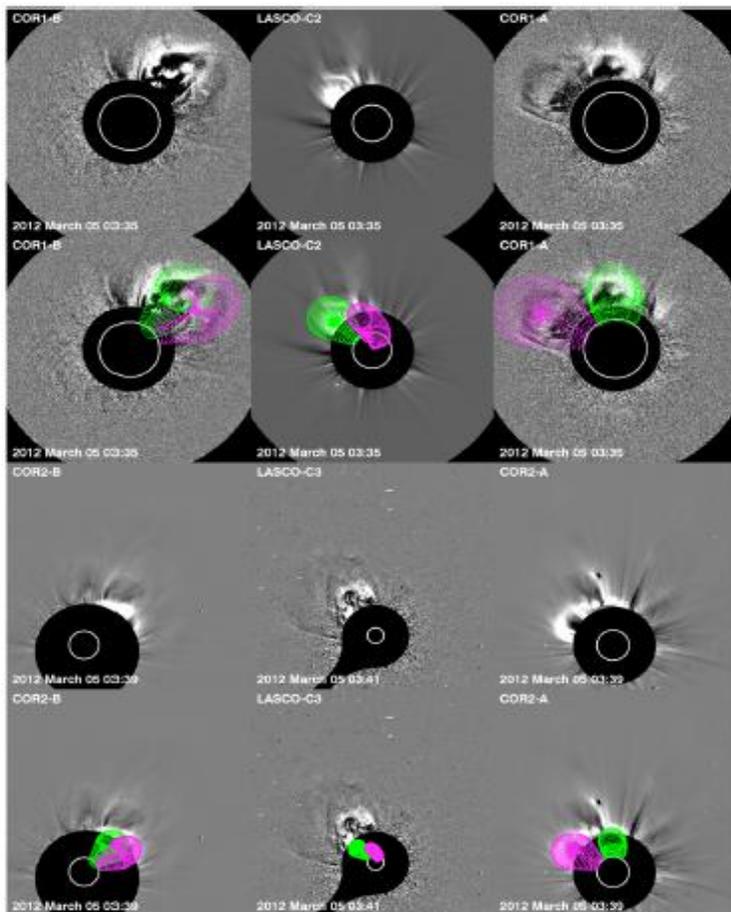


Figure 3. Contemporaneous observations of CME-1 and CME-2 in all six coronagraphs from STB (left), LASCO (center), and STA (right) before the eruption of CME-3. The GCS fits suggest that the CMEs do not interact. CME-1 (magenta) and CME-2 (green) are observed at 4.4 and $4.1 R_{\odot}$, respectively.

图 7. 45: CME-3 出现前的 CME-1 和 CME-2

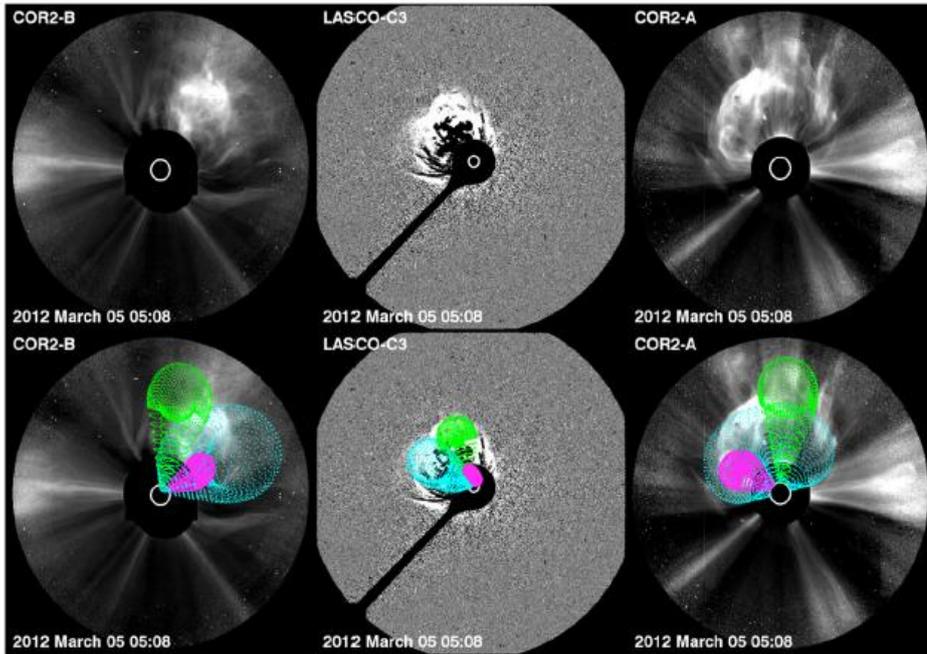


Figure 6. Interaction of CME-3 (blue) with CME-1 (magenta) and CME-2 (green) at 6.8, 13.4, and 13.1 R_{\odot} , respectively. The separate fronts of all three CMEs are most evident in the COR2-A (top right).

图 7. 46: 在 6.8, 13.4, and 13.1 R_{sun} 三个不同高度 CME-3(蓝)与 CME-1(紫) 和 CME-2(绿) 的相互作用

7.3. 主要科学贡献

NOAA11429 事件产生了 2 个 X 级、13 个 M 级耀斑及太阳质子事件，并伴有全晕 CME 事件，重点研究内容包括：大耀斑案例(X5.4)、全晕 CME 及其演化、大黑子演化、源区和爆发间的关系、CME 之间的相互作用及高能粒子事件。

● 现象及参量研究

➤ 耀斑期间磁瞬变

分析了 NOAA 11429 活动区 M7.9 耀斑期间的磁图、多普勒图、强度图、Stokes I 和 V 轮廓，在耀斑起始，负通量的瞬变快迅速出现在正极性的半影内，讨论了这是磁场结构真实的变化还是仪器影响，认为这是磁场的真实变化。

➤ 一对大日冕物质抛射出现前封闭耀斑期间磁绳的形成

利用非线性无力场外推方法，发现了两个分离、弱缠绕磁绳系统，说明磁绳爆发前的存在最终形成两 CME 的种子。

➤ NOAA 11429 活动区的面积与倾角

利用沙特阿拉伯国王大学天文台 (AOKSU)白光像研究了 NOAA 11429 活动区的黑子群面积与倾角，面积显示三个相位，面积与倾角紧密相关

➤ 大耀斑期间光球磁场与洛伦兹力矢量的突然变化

分析了 SDO 观测到的六个大耀斑期间光球磁和洛伦兹力的空间及时间变化，中性线场矢量变得更强、更水平，这几乎是水平场分量与中性线平行性的增强结果；耀斑前中性线场比势场线更垂直、突然塌缩、更接近势场倾角，说明与非势场倾角相关的磁张力松弛在大耀斑期间起了重要作用，而剪切角并没有显示这种形状，水平场变得更加显著且与中性线更对齐；在耀斑期间，洛伦兹力有一个大的、突然永久的向下变化；水平洛伦兹力的行为变化在两侧以相反的方向更平行于中性线，把中性线两侧拉得更靠近。

➤ 超级活动区 11429 磁绳的 Twist 和 Writhe

分析 NOAA 11429 活动区的磁螺度、磁通、螺度积累、倾角的演化，磁螺度通量与倾角似乎是时间相关的，当倾角减少而负磁螺度积累时，在第一观测阶段，耀斑/CME 事件活动较高。

➤ NOAA11429 活动区声晕的声学发射增强

利用高频 p 模谱的声学全息像分析了 NOAA11429 活动区声晕的声学发射增强，发现在中等场强度区声源明显增强，在活动区于晕之间识别出了一个转换区，声源能量被中等场强的倾斜场阻碍了。

● 非线性无力场外推

通过非线性无力场外推方法分析了 NOAA11429 活动区两个连续耀斑爆发并研究了其磁重构，在耀斑爆发期间磁自由能向下跳跃了 20-30%，磁螺度注入率的符号改变可能与爆发有关，磁场“爆炸”现象与第一个 X 耀斑的发生紧密相关。

● CME 特性研究

➤ 两个大 CME 事件前兆研究

利用微分发射量(DEM)识别出了通量绳及主活动区的发射分量，跟踪了前

者的时间演化,对 NOAA 11429 活动区两个快速 CME 爆发前的形状进行了分光
谱分析。第一个 CME 出现 5 小时前,东侧区域的时间演化显示平均 DEM 增加
了一个量级,这与蓝移和非热速度增加显示的通量绳的逐步上升及加热有关,观
测到通量绳的整体向上运动。

➤ 从太阳到日球层顶 CME 的传播

分析了 NOAA 11429 活动区产生的一系列 CME 事件,在地球附件观察到了一
族激波事件及行星 CME 事件,瞬变流相互作用抹去了源的记忆并与前导激波
形成了一个混合相互作用区(MIR)。

➤ 2012 年 3 月 5 日三个 CME 之间的相互作用

运用向前拟合方法分析了发生在 2012 年 3 月 5 日三个 CME 之间的相互作
用及运动行为,当第二个 CME (CME-2) 在 02:45UT 从东边缘出现时第一个
CME (CME-1)已经在继续,这两个 CME 没有相互作用,直到第三个 CME(CME-3)
在 03:34 UT 从 NOAA11429 活动区爆发,速度为 $1456[\pm 31]$ km/s 的 CME-3 驱
动了以激波,CME-3 驱动的激波通过 CME-1 时没引起后者在几何、轨迹及速度
的改变,然而,当 CME-1 到达地球时在原地探测到的温度升高显示 CME-1 内的
等离子体可能被激波的通过加热了,CME-2 被 CME-3 加速了两次以上,在 CME-3
之前保持了独立的结构,CME-2 的 40 度偏角中有 24 度是由 CME-3 引起,说明
CME-2 和 CME-3 的碰撞时超弹性的。

● 方法研究

➤ 自动跟踪黑子群

基于集合与图形操作发展了一种在一系列连续太阳图像中发现和跟踪黑子
群样体及其属性(位置、面积、磁场、强度等)的方法。在本影族的磁场族中发
现了短暂的顺变及长久的变化,靠近极性翻转线(PIL)两侧相对的两个小本影族
显示视场磁场的阶梯突变,正极性族减少,而负极性族增加,一些大型本影族在
耀斑期间黑度也显示突然减少。作为被推向相反磁性半影区长、窄磁条的一部分,
本影族可能是一些耀斑的触发原因,两个大的反极性本影族经历剪切与收缩运
动,这些族运动曲线的破裂及转点与耀斑有关。

➤ 像素动力分析法

Rasca 等 (2016, APJ, 832, 53) 提出了一种像素动力分析法, 发现光球吸收线谱的轮廓, 确定线移、宽度、非对称性及峰值的变化, Fe I 6301.5Å 谱的线宽与峰值变化与 NOAA 11429 的 M7.9X 耀斑存在明显的空间及时间关系。

➤ 黑子面积时间演化与相关等离子体流估计

运用模糊集计算了几个活动区的黑子本影及半影面积、增长极衰退率, 一个经验的非旋转、均匀汇聚水平速度场与轴对称、随高度不变磁场的相关作用产生了黑子内非常复杂的对流特征。

● 对地效应

2012 年 3 月 7-11 日地球空间经历了大量的高强度空间天气现象, 包括地 24 太阳活动周的第二大磁暴, 观测到超低频波增强、辐射带相对论电子逃逸、及强能量电子注入, 这些现象最终与两个超快 CME(>2000 km/s)和两个 X 级耀斑相连。发现只有第二个 CME 指向地球, 分析了到的地球的 ICME 磁场等性质。

7.4. 其它

7.4.1. 其它参考文献

参见第六章 6.2.6.2.6 六个大中性线耀斑光球磁场与洛伦兹力矢量的突变, p. 错误! 未定义书签。

7.4.2. 观测影像资料

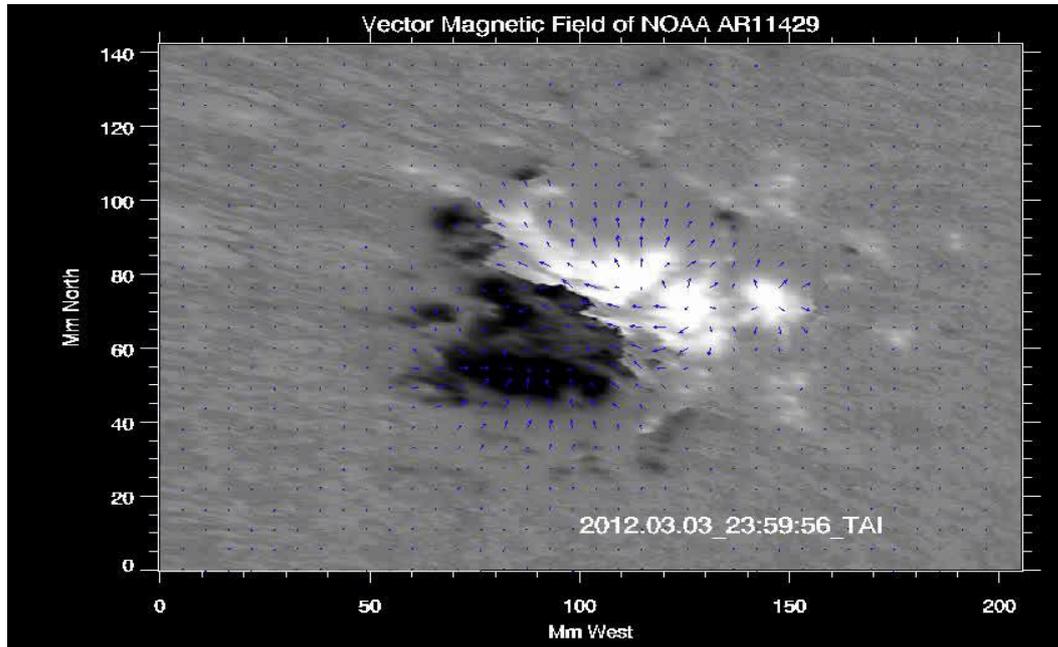


图 7. 47: 2012 年 3 月 3 日 HMI 观测 NOAA 11429 活动区的磁场演化([Chintzoglou, 2015, APJ, 809, 34](#))

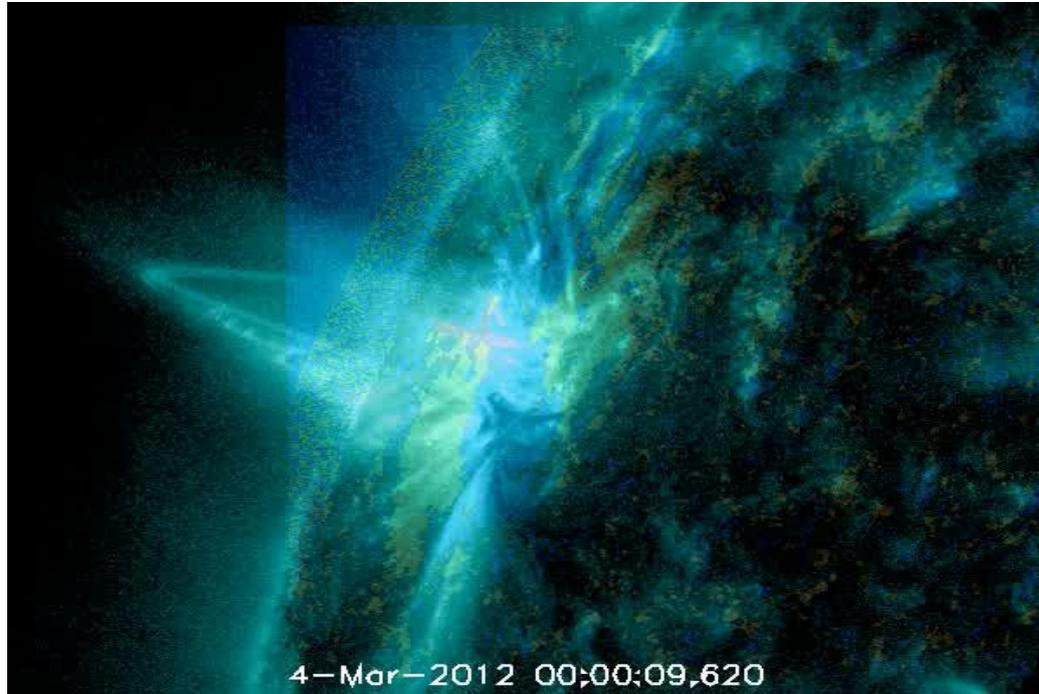


图 7. 48: 2012 年 3 月 4 日 AIA/131Å 观测 NOAA 11429 活动区演化([Chintzoglou, 2015, APJ, 809, 34](#))

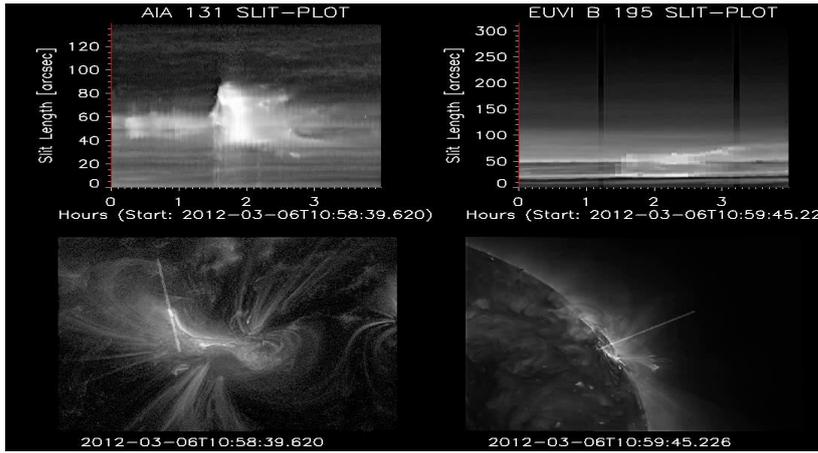


图 7. 49:2012 年 3 月 6 日 AIA131、195Å观测 NOAA 11429 活动区演化([Chintzoglou, 2015, APJ, 809, 34](#))

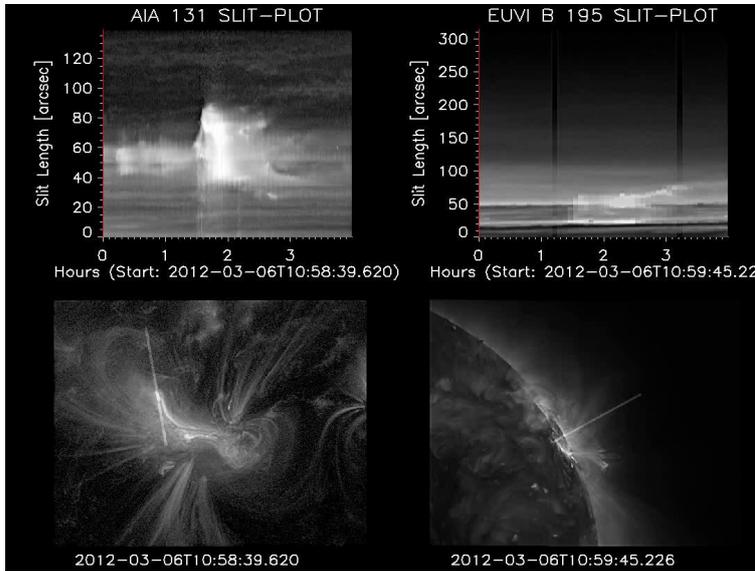


图 7. 50:2012 年 3 月 6 日 STEREO B/EUVI at 195 Å观测 NOAA 11429 活动区演化([Chintzoglou, 2015, APJ, 809, 34](#))

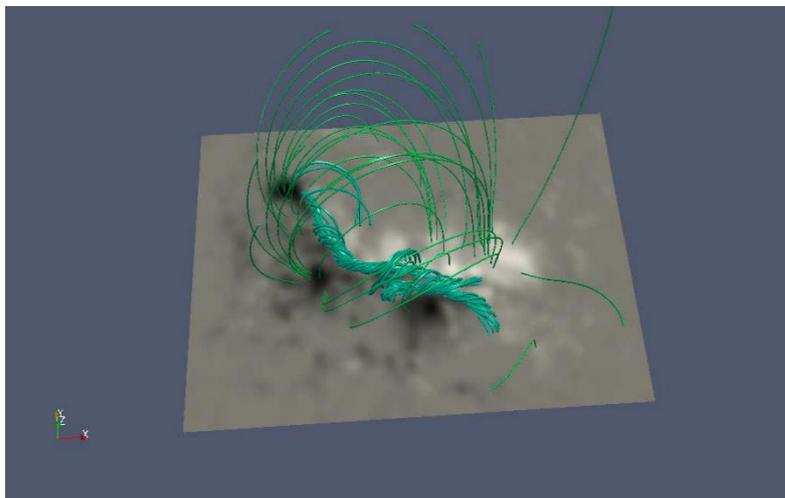


图 7. 51: 2012 年 3 月 6 日 NLFFF 磁场外推([Chintzoglou, 2015, APJ, 809, 34](#))

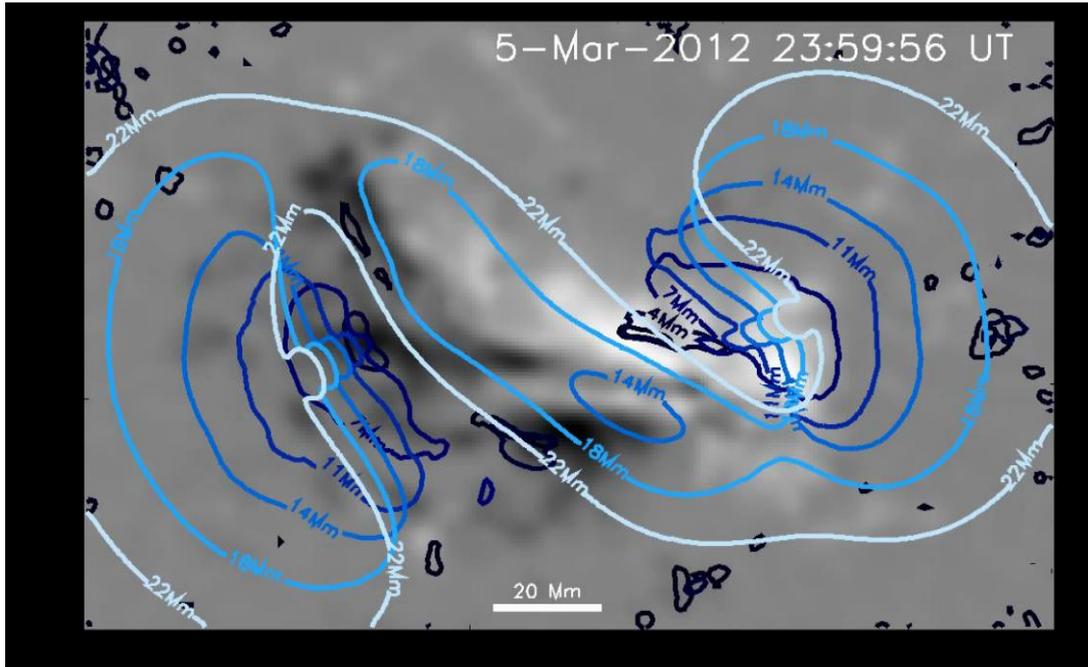


图 7. 52: 2012 年 3 月 1 日 STEREO 观测(Liu, 2014 , APJL, 788:L28)



图 7. 53: 2012 年 3 月 1 日 STEREO 观测(Liu, 2014 , APJL, 788:L28)



图 7. 54: HMI 观测 NOAA 11429 活动区的磁场演化 ([Elmhamdi, 2014, Solar Phys., 289, 2957 - 2970](#))

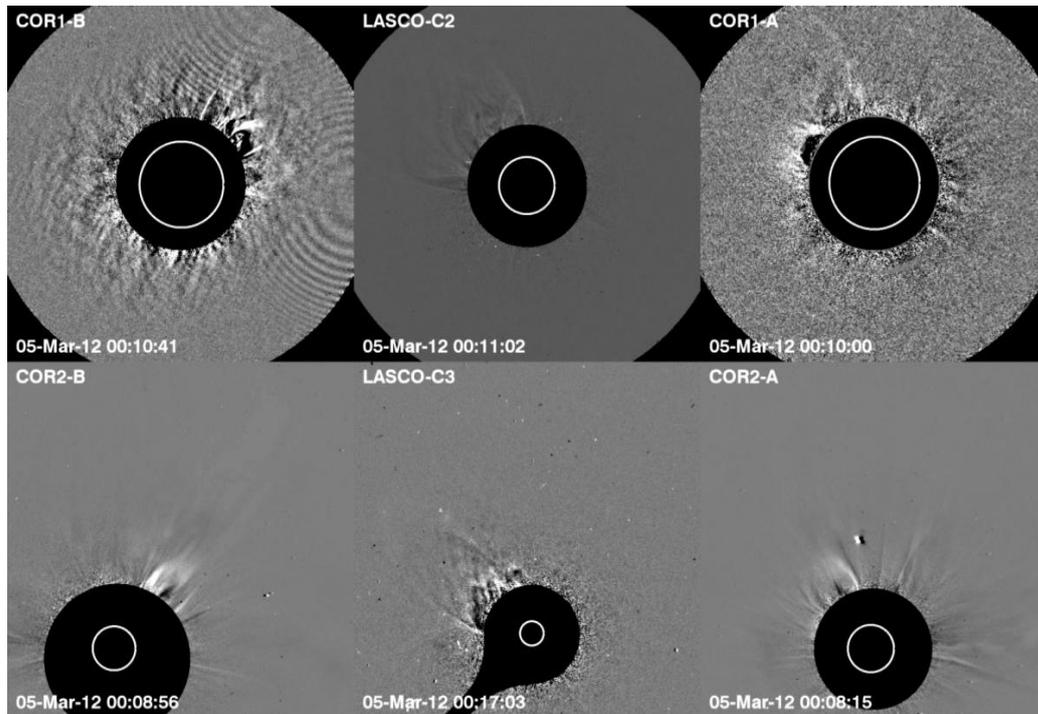


图 7. 55: NOAA 11429 CME ([Colaninno, 2015, APJ, 815, 70](#))

7.5. 主要参考文献

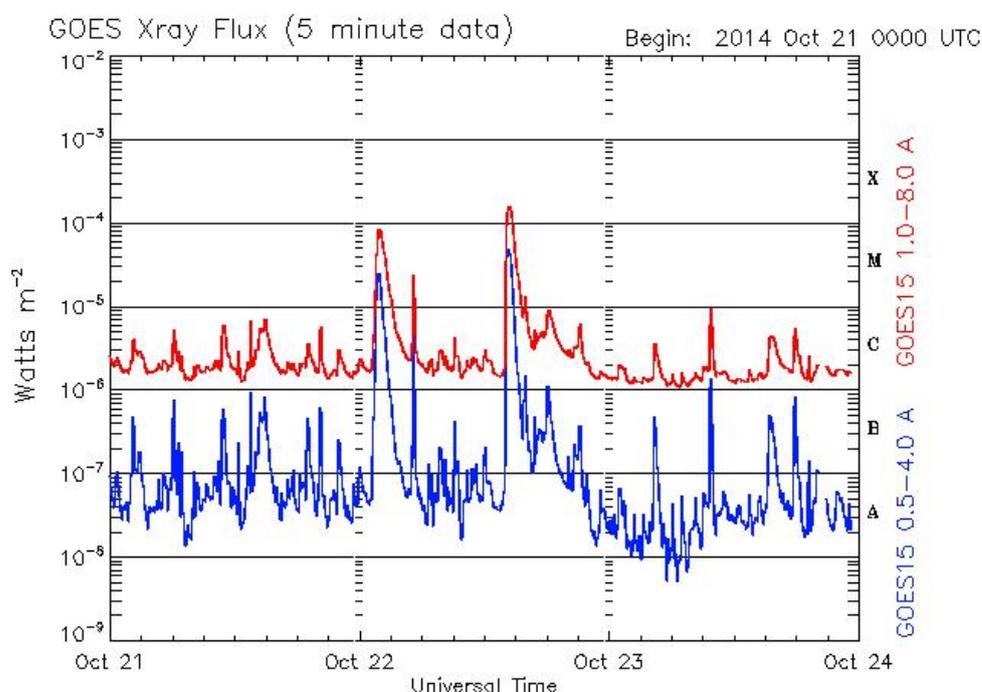
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第八章 NOAA 12192 活动区事件

8.1. 事件概述

NOAA12192 活动区 2014 年 10 月 17 日转入可视日面，随即变成巨大的活动区，在 10 月 24 日，面积达到最大值 2740，其后非常缓慢下降，一直到 10 月 31 日转出可视日面，也具有较大的面积，其寿命超过太阳的半个自转周。12192 活动区处于第 24 周黑子相对数峰值（58）附近。该活动区磁场位型非常复杂，其在太阳可视日面存在的时间内，磁分型均为 Beta-Gamma-Delta, McIntosh 分型为最强的 Fkc，暗示其可能存在频繁大规模爆发的可能。NOAA12192 活动区是过去 24 年以来最大的活动区，产生了不寻常的 100 多个耀斑，包括 32 个 M 级及 6 个 X 级，但只有一个小 CME 事件，没有太阳高能粒子事件，也没有地磁暴。



Updated 2014 Oct 23 23:30:12 UTC

NOAA/SWPC Boulder, CO USA

图 8. 1: NOAA12192 活动区 GOES 流量图

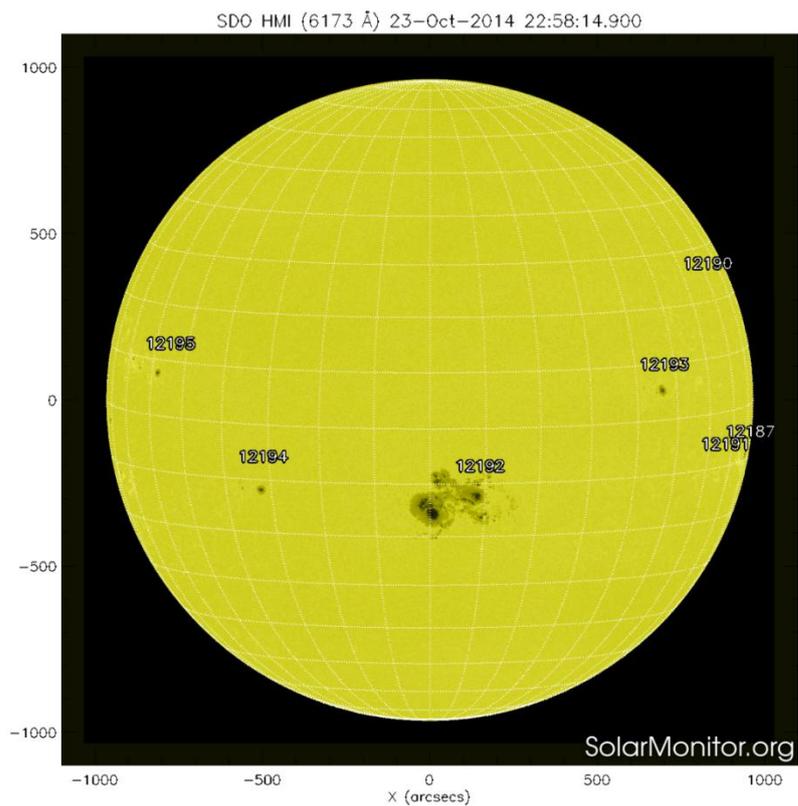


图 8. 2: NOAA12192 活动区全日面黑子图

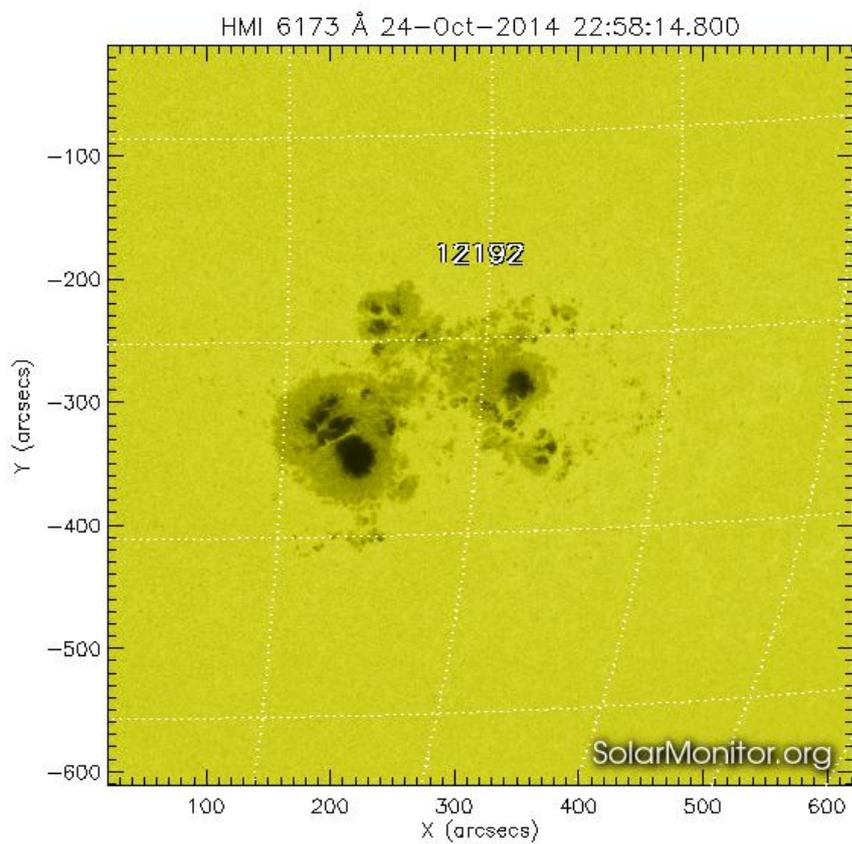


图 8. 3: NOAA12192 活动区 HMI 局部磁图

8.1.1. 事件特征

- 事件观测时间：2014 年 10 月 17 日转入可视日面，10 月 31 日转出可视日面
- 最大面积：2740；时间：2014 年 10 月 24 日；位置：S14W06
- 磁位型： $\beta\gamma\delta$
- X 级耀斑数量：6
- M 级耀斑级别：32
- 最大耀斑级别：X3.1；时间：2014 年 10 月 24 日 21:15UT；位置：S16W21
- 高能粒子事件：无
- CME 事件：只在一次 M 级耀斑中伴随了一次非常小的窄 CME
- 对地效应：地磁指数：Dst=-50, kp=5（10 月 20 日）

表 8.1: NOAA 12192 活动区的 X 和 M 级耀斑

Table 1
X- and M-class Flares in Solar AR 12192

Event	Date	Start Time (UT)	Peak Time (UT)	Duration (minutes)	GOMC Level	Location in AR	CME Production	Other Activities
X-class Flares:								
X01	2014 Oct 19	04:17	05:03	91	X1.1	core	No	—
X02	2014 Oct 22	14:02	14:28	48	X1.6	core	No	—
X05	2014 Oct 24	21:07	21:41	66	X3.1	core	No	—
X04	2014 Oct 25	16:55	17:08	76	X1.0	core	No	—
X09	2014 Oct 26	10:04	10:56	74	X2.0	core	No	—
X06	2014 Oct 27	14:12	14:47	57	X2.0	core	No	—
M-class Flares:								
M01	2014 Oct 18	07:02	07:58	107	M1.6	core	No	—
M02	2014 Oct 20	09:00	09:11	20	M3.9	core	No	—
M05	2014 Oct 20	16:00	16:37	55	M4.5	core	No	—
M04	2014 Oct 20	18:55	19:02	9	M1.4	periphery (L1 ^a)	No	jet
M05	2014 Oct 20	19:53	20:04	20	M1.7	core	No	—
M06	2014 Oct 20	22:43	22:55	30	M1.2	core	No	—
M07	2014 Oct 21	13:35	13:38	5	M1.2	periphery (L1)	No	jet
M08	2014 Oct 22	01:16	01:59	72	M0.7	core	No	—
M09	2014 Oct 22	05:11	05:17	10	M2.7	core	No	—
M010	2014 Oct 23	09:44	09:50	12	M1.1	core	No	—
M011	2014 Oct 24	07:37	07:48	16	M4.0	periphery (L2 ^b)	Yes	jet
M012	2014 Oct 26	17:08	17:17	22	M1.0	core	No	—
M013	2014 Oct 26	18:07	18:15	13	M4.2	core	No	—
M014	2014 Oct 26	18:43	18:49	13	M1.9	core	No	—
M015	2014 Oct 26	19:59	20:21	46	M2.4	core	No	—
M016	2014 Oct 27	00:06	00:34	38	M7.1	core	No	—
M017	2014 Oct 27	01:44	02:02	27	M1.0	core	No	—
M018	2014 Oct 27	03:35	03:41	13	M1.3	core	No	—
M019	2014 Oct 27	09:59	10:09	27	M6.7	core	No	—
M020	2014 Oct 27	17:33	17:40	14	M1.4	periphery (L2)	No	jet
M021	2014 Oct 28	02:15	02:42	53	M3.4	core	No	—
M022	2014 Oct 28	03:23	03:32	18	M6.6	core	No	—
M023	2014 Oct 28	13:54	14:06	29	M1.6	core	No	—
M024	2014 Oct 29	06:03	06:20	169 ^c	M1.0	core	No	—
M025	2014 Oct 29	09:54	10:01	12	M1.2	periphery (L2)	No	—
M026	2014 Oct 29	14:24	14:33	27	M1.4	core	No	—
M027	2014 Oct 29	16:06	16:20	27	M1.0	core	No	—
M028	2014 Oct 29	18:47	18:50	5	M1.3	core	No	—
M029	2014 Oct 29	21:18	21:22	7	M2.3	core	No	—

Notes.

^a Marked by the yellow circle in Figure 1(a).

^b Marked by the yellow circle in Figure 1(d).

^c The unorthodox long duration is due to multiple energy releases.

8.1.2. 观测特征

- 从10月17日至10月31日，该活动区爆发了127个C级及以上耀斑，其中包括6个X级耀斑和32个M级耀斑，其中最大的为X3.1级。
- 在该活动区爆发的数次强耀斑中，几乎没有伴随CME，只在一次M级耀斑中伴随了一次非常小的窄CME，而且没有对地效应。
- 这个活动区最显著的特点是面积巨大，结构复杂，耀斑频发，且不伴随CME，成为学界研究的热点。

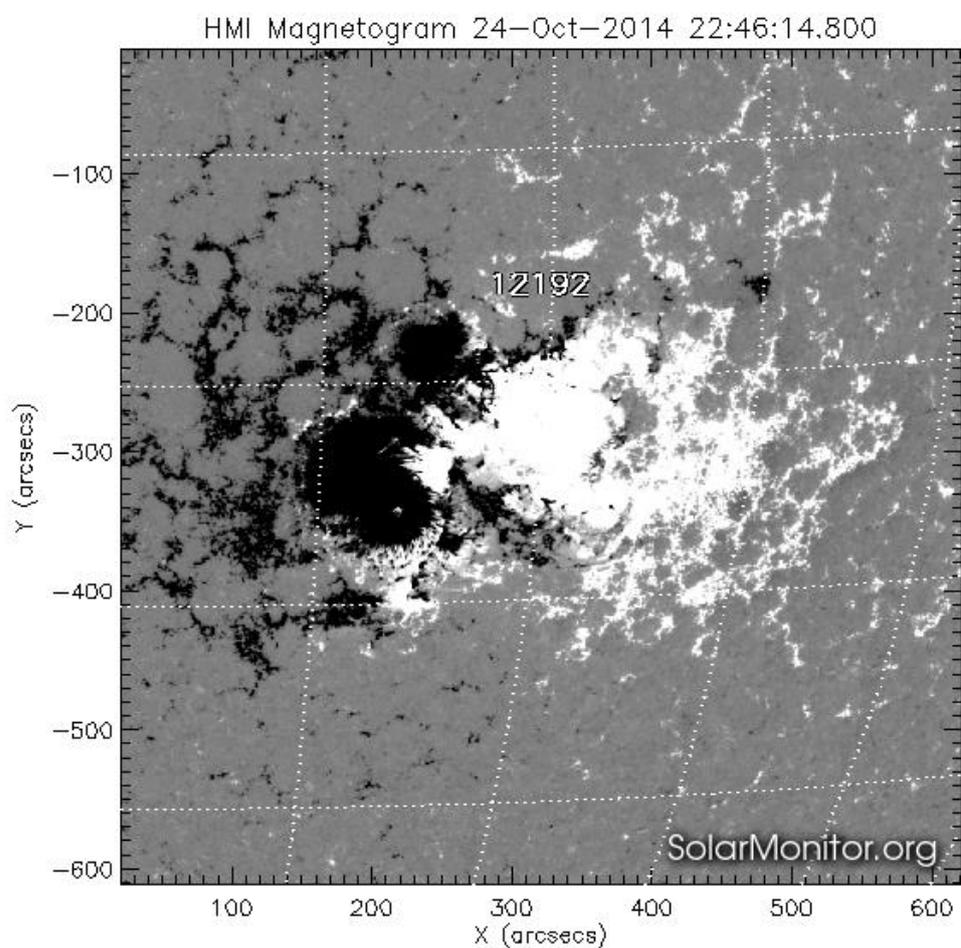


图 8. 4: 12192 磁图(SDO/MHI)

8.2. 相关事件案例研究

与该事件有关的研究论文有 40 篇，大多数论文都是围绕着耀斑频发且不发生 CME 的论点出发，从观测，模拟，外推等多角度尝试阐述这个原因。

8.2.1. 为什么 12192 大活动区是富耀斑而贫 CME?

孙旭东等 (2015, ApJL, 804, L28) 分析了富耀斑而贫 CME 的 NOAA12192 活动区阻止爆发的磁场条件及相关后果，发现与其他两个产生大耀斑/CME 的活动区 (11429 和 11158) 相比，12192 是“大而温和”的活动区，其核区显示较弱非势性、较强的背景场、与耀斑相关的较小的场变化，这些差异存在于密集型指数（例如平均）中，但通常不是在宽泛指数（例如总数）中。12192 活动区大量自由磁能没有转变为产生 CME。这些意外行为显示活动区爆发被一些磁非势相对量限制，被限制的耀斑可能离开较弱的光球和日冕特征。（希望设计出一种新的量度来判断爆发性（eruptiveness），将来可以用来做 CME 的预报。）

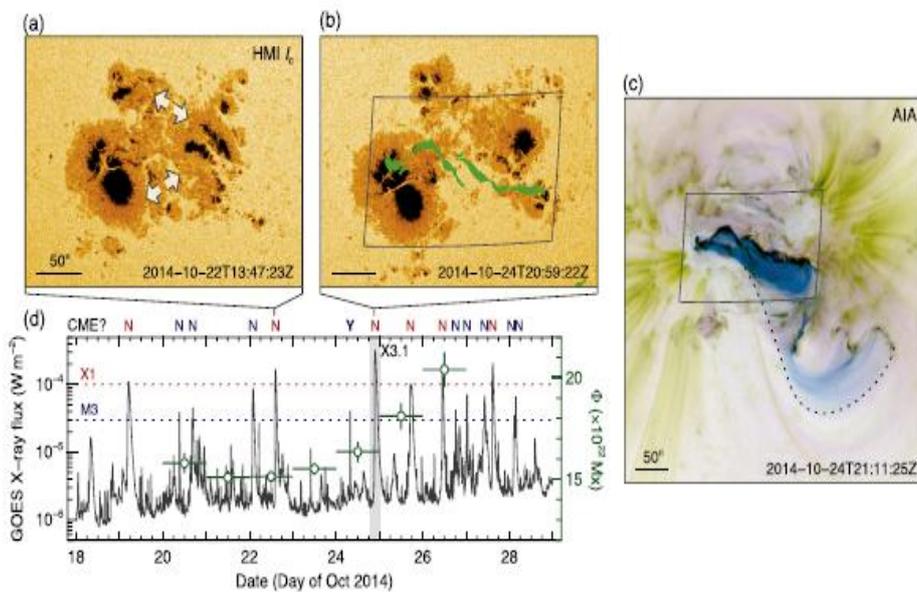


Figure 1. Overview of AR 12192. (a) and (b) HMI continuum intensity before two X-class flares with scattered light removed. Arrows in (a) denote two locations where significant sunspot separation took place. AIA 1600 Å ribbons for the X3.1 flare are overlotted in (b). (c) Negative composite AIA image during the X3.1 flare. Cyan, yellow, and magenta show 131, 171, and 335 Å passbands, respectively. Dotted curve outlines the hot 131 Å loops connecting the main flaring site to the southwest. Boxes in (b) and (c) define the extent of Figure 2(a). (d) GOES 1–8 Å flux (black) and unsigned magnetic flux Φ (green symbols). The AR passed central meridian on October 23. CME production of each major flare is marked along the top. Horizontal error bars of Φ indicate a 1 day window; vertical error bars indicate daily standard deviation.

图 8. 5: HMI 强度图 (a, b)、负 AIA 图 (磁 c)、GOES 流量 (d)

表 8.2: 三个活动区 NOAA 12192、11429 及 11158 磁场特征比较

Table 1
Comparison of Magnetic Characteristics of Three Major Active Regions

		AIR 12192	AIR 11429	AIR 11158	Unit	Type ^a		
Flare and CME ^b	Flare index	2335	1295	592				
	Major flare	15	7	3				
	Event	SOL2014-10-24T21:41	SOL2012-03-07T00:24	SOL2011-02-15T01:56				
	Location	S21W21	N18E31	S20W10				
	GOES class	X3.1	X5.4	X2.2				
	Duration	66	38	22	minutes			
	CME	No	Yes	Yes				
Photosphere ^c	Overall	Sunspot area	4002 ± 11	1490 ± 2	861 ± 4	μMm	<i>E</i>	
		ϕ	16.12 ± 0.08	4.88 ± 0.04	2.75 ± 0.04	10 ²³ Mr	<i>E</i>	
		I	25.96 ± 0.08	8.00 ± 0.03	6.31 ± 0.03	10 ²³ A	<i>E</i>	
		log R	5.30 ± 0.01	5.32 ± 0.01	4.89 ± 0.01	—	<i>E</i>	
	FPL	Mask area	357 ± 4	231 ± 2	224 ± 10	μMm	<i>E</i>	
		ϕ	0.31 ± 0.03	0.45 ± 0.03	0.28 ± 0.04	10 ²³ Mr	<i>E</i>	
		I	1.10 ± 0.08	1.35 ± 0.03	1.12 ± 0.03	10 ²³ A	<i>E</i>	
		R (mm)	453 ± 3	827 ± 4	676 ± 14	G	<i>I</i>	
		I (mm)	16.1 ± 0.3	30.7 ± 0.6	27.7 ± 0.4	mA m ⁻²	<i>I</i>	
		Stellar	50.2 ± 0.3	57.9 ± 0.3	60.1 ± 0.7	degrees	<i>I</i>	
		α	0.05 ± 0.00	0.19 ± 0.00	0.25 ± 0.01	Mm ⁻¹	<i>I</i>	
		Current helicity	0.72 ± 0.04	6.74 ± 0.06	5.26 ± 0.23	G ² m ⁻¹	<i>E</i>	
	Low corona ^d	Overlying	$B_z(42)$	220 ± 8	61 ± 7	42 ± 0	G	<i>I</i>
			$B_z(42)/B_z(2)$	0.35 ± 0.04	0.06 ± 0.00	0.05 ± 0.00	—	<i>I</i>
Critical height			77 ± 1	34 ± 0	42 ± 1	Mm	<i>I</i>	
Energy		F_T	152.6 ± 0.2	20.9 ± 0.1	8.8 ± 0.0	10 ²² erg	<i>E</i>	
		F_J	4.5 ± 0.0	10.6 ± 0.0	2.5 ± 0.0	10 ²² erg	<i>E</i>	
		K_J/K_T	0.03 ± 0.00	0.51 ± 0.02	0.28 ± 0.01	—	<i>I</i>	
Change ^e	ΔK_T	-0.90	-1.58	-0.26	10 ²² erg	<i>E</i>		
	$\Delta(\sum B_z \delta A)$	+1	+14	+8	10 ²⁰ Mr	<i>E</i>		
	$\Delta(B_z)$	+11	+200	+129	G	<i>I</i>		
	ΔK_z	+02	+11.1	+4.7	10 ²¹ dyn	<i>E</i>		
	Topology change	Small	Large	Large	—	<i>I</i>		

^a Indices are classified as extensive (*E*) or intensive (*I*); see Section 3.1. Indices in bold are arbitrarily selected as examples for each category.

^b Flare index is defined as $\sum 100M_1 + \sum 10M_2 + \sum M_3$, where M_i indicate the GOES magnitude of each X-class flare, etc. Major flares include those above M3, between E20 and W70.

^c Sunspot area is computed from DN11 intensity, including both umbra and penumbra. R measures the total unsigned flux within 15 Mm of high-gradient FPL (Schrijver 2007), here with B_z instead of line-of-sight maps. Mean shear is the mean angle between the observed and the modeled FPL on the photosphere; mean toroidal parameter α is calculated as $\sum B_z I_z / \sum B_z^2$; current helicity is approximated by $(\sum B_z I_z)$ (Hoara et al. 2014).

^d The overlying field refers to B_z directly above the FPL in the FPL model. $B_z(42)$ indicates mean B_z at 42 ± 1 Mm, typical height of eruption onset (Liu 2008). $B_z(42)/B_z(2)$ is the mean ratio of B_z at 42 ± 1 and 2 ± 1 Mm (cf. Wang & Zhang 2007). The critical height is where the B_z decay index n reaches 1.5 so the ions instability may set in (Klein & Török 2008).

^e The change of the surface integral $\sum B_z \delta A$ and the mean $\langle B_z \rangle$ consider the FPL region only, where δA is the pixel area. The change of “Lorentz force” F_z refers to the change of $\sum (B_z^2 - B_z^2) \delta A / (4\pi)$ within FPL (Parker et al. 2012). Topological change is assessed qualitatively based on Q and coronal field connectivity (Figure 3).

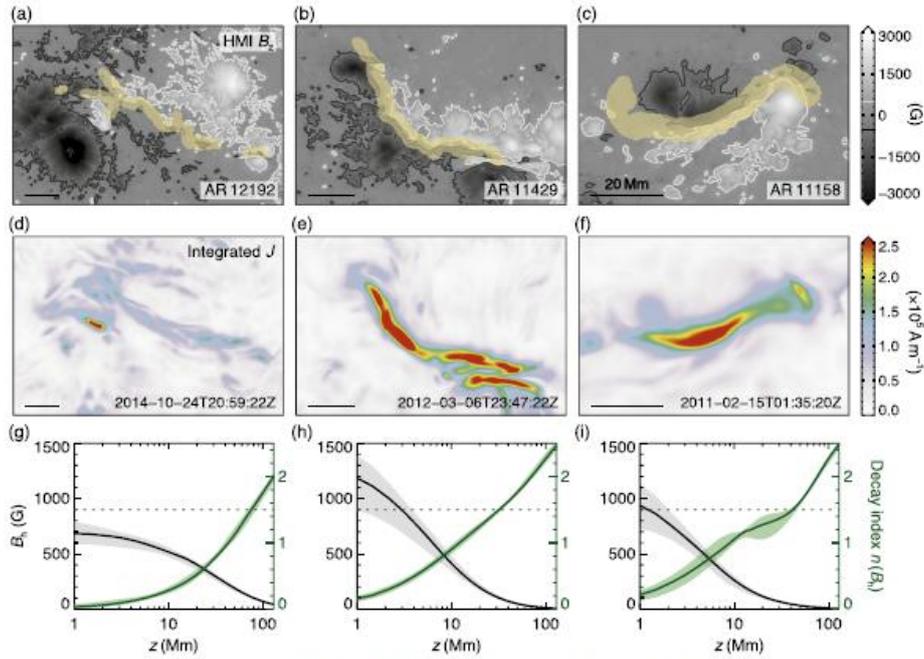


Figure 2. Comparison of pre-flare magnetic conditions of AR 12192, 11429, and 11158 prior to their respectively largest flare. (a)–(c) B_z maps of the core region. They are 164, 120, and 76 Mm respectively in width. The yellow shaded regions denote our FPIL masks. (d)–(f) Maps of the vertically integrated J over the lower 11 Mm in the NLFFF model. (g)–(i) Height profile of B_z (black) and decay index n (green) above the FPIL in the PF model. A total of $1\text{--}2 \times 10^3$ profiles are evaluated for each AR; outliers are removed by using a K -mean algorithm. Lines show the median; shaded bands indicate 1σ spread. Horizontal dotted line indicates the critical value $n = 1.5$. In (i), the kink (cf. Nindos et al. 2012) and the larger spread of n are due to the quadrupolar nature of AR 11158 (only the central bipole is shown); magnetic connectivity changes rapidly at 10–40 Mm.

图 8. 6: NOAA 12192, 11429 和 11158 耀斑前磁状态比较。(a) - (c) 核心区磁图 B_z (上)、NLFFF 模型在较低 11Mm 计算的垂直积分电流 (中)、势场 (PF) 模型中耀斑极性翻转线(FPIL)上方 B_z h(黑)与衰变指数 n (绿)的高度轮廓

8.2.2. 2014 年 10 月 18 到 29 日 NOAA 12192 活动区的限制耀斑

陈华东等 (2015, ApJL, 808, L24)采用 SDO AIA 及 HMI 数据, 分析了 2014 年 10 月 18 到 29 日 NOAA 12192 活动区的 6 个 X 级和 29 个 M 级耀斑, 其中 30 个 (包括 6 个 X 级) 起源于活动区核, 其它 5 个出现在活动区周边。4 个 X 耀斑显示相似的耀斑结构, 说明它们是具有相似触发机制的同源耀斑, 可能的场面是浮现磁通的光球运动导致相关日冕磁场的剪切, 从而产生有利于 tether-cutting 构型。在 5 个周边的 M 级耀斑中个个与喷流 (jet) 活动有关, HMI 垂直磁场显示, 耀斑出现之前相关极性的光球磁场在 jet 的足点浮现、汇聚与对消。活动区周边只有一个 M 级耀斑之后跟随 CME。在 20 至 26 日期间, 在 40 - 105 Mm 高度之间水平背景磁场的平均衰减指数小于 torus 不稳定性触发的典型阈值, 对磁场的强限制可能是 12192 活动区贫 CME 产生的原因。

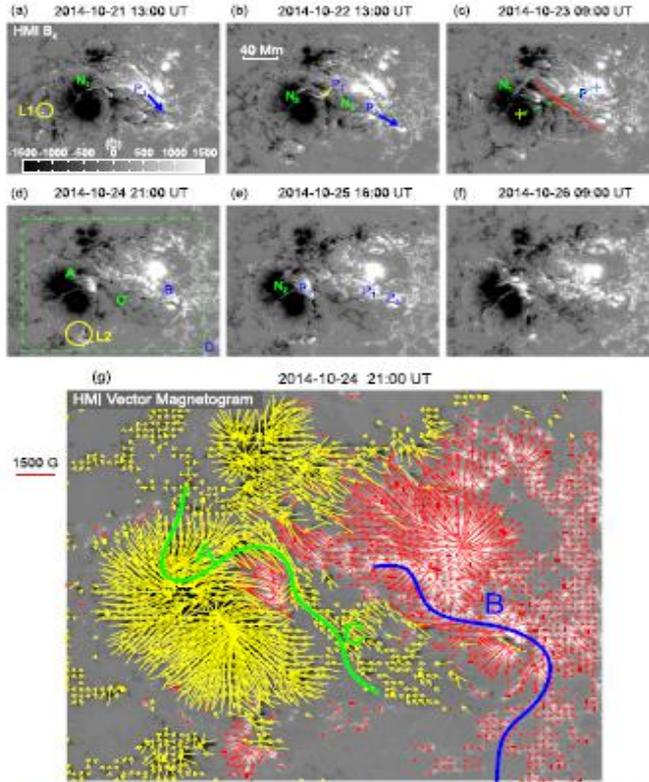


Figure 1. [(a)-(f)] HMI B_z map (also see animation 1); (g) HMI vector magnetic field map. The blue thick arrow in panels (a) and (b) indicate the shearing motions of the fluxes Φ_1 and Φ_2 . The yellow thin arrow in panel (b) points to the location of Φ_2 . The yellow, blue, and red plumes in panel (c) correspond to the locations of the maximum negative flux, maximum positive flux, and their midpoint, respectively. The red line in panel (c) is the reference line along which we calculated the decay index n . The circles in panels (a) and (d) mark the two locations L1 and L2, respectively. The dashed box in panel (d) indicates the XUV of panel (g). The green and blue curves in panel (g) indicate the principal shape of the flux ribbons around the peak time of XUV. (An animation of this figure is available.)

图 8.7: (a) - (f) HMI B_z 图, (g) HMI 矢量磁图

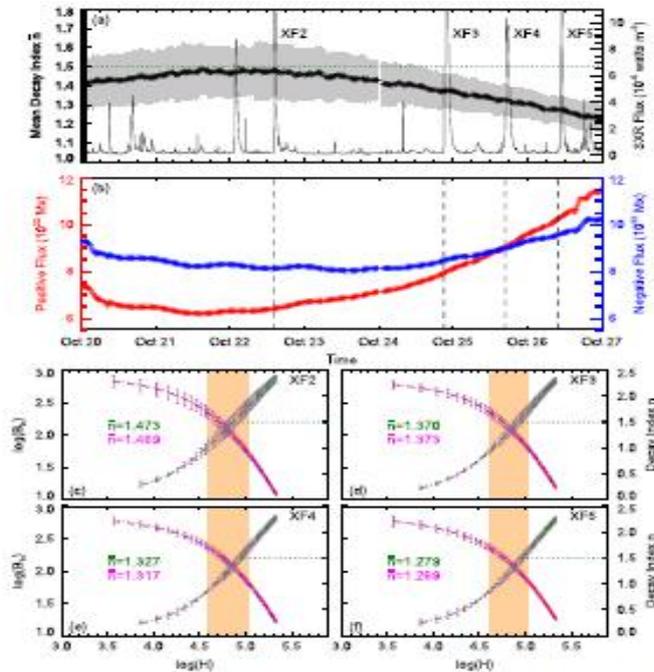


Figure 4. (a) Time variations of the mean decay index n (plus) with 1 σ uncertainty (shaded line) and GOES soft X-ray (SXR) flux (curve); (b) time profiles of the positive (red plus) and unsigned negative (blue plus) vertical fluxes of AR 12192; [(c)-(f)] height profiles of B_z with 1 σ error bars before (blue dashed line) and after (red dashed line) 30°-30° height variations of decay index n with 1 σ error bars before (green solid line) and after (purple dotted line) the flare 30-min. Horizontal dotted lines in panels (a) and (d)-(f) indicate the lower limit ($n = 1.5$) of the threshold for torus instability onset. The vertical lines in panel (b) indicate the start times of XUV-XUV. The orange regions in panels (c)-(f) mark the height range of 40-115 Mm.

图 8.8: (a) 平均衰变指数(阴影线) GOES SXR 流量; (b)正与负垂直通量; (c) - (f) XF2 - XF5 前(蓝)后(红) B_h 的高度轮廓。虚线表示 torus 不稳定性阈值的底限 ($n=1.5$)

8.2.3. 在太阳黑子亮桥上方摆动的亮墙

杨书红等 (2015, ApJL, 804, L27)通过 IRIS 和 NVST 对 NOAA12192 活动区的联合观测, 辨别出在亮桥(Light Bridge)上面存在着很多亮墙结构(Light Wall), 在 1330, 171 及 131 Å 谱线, 墙顶点较亮, 而在 H α 谱线, 墙顶辐射较低。墙顶上下运动形成震动, 震荡的平均高度、振幅、速度及周期分别为 3.6 Mm、0.9Mm、15.4 km/s 和 3.9 分钟, 暗示其可能来自于光球下 P 模的泄露。

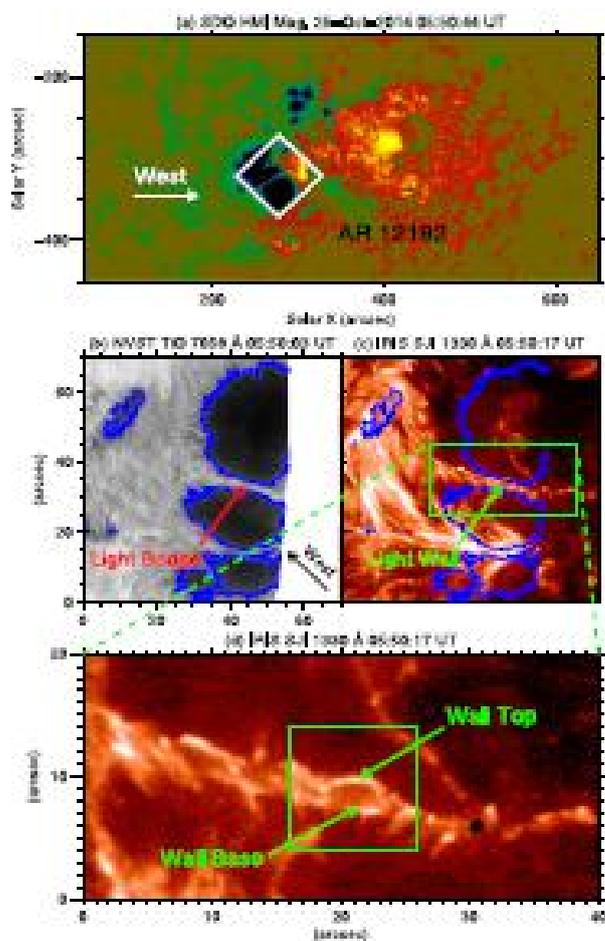


Figure 1. Panel (a): SDO HMI line-of-sight magnetogram displaying the overview of AR 12192. Panels (b) and (c): NVST TiO 7058 Å and IRIS SJI 1330 Å images (also see animation 1) showing the light bridge and the light wall in the FOV outlined by the square in panel (a). The blue curves in panels (b) and (c) are the contours of the sunspot umbra. Panel (d): expanded view of the 1330 Å image outlined by the rectangle in panel (c). The square outlines the FOV of Figures 2(a)–(d).
(An animation of this figure is available.)

图 8. 9: 亮桥与亮墙, SDO HMI 视向磁图(a), NVST TiO 7058 Å (b) , IRIS SJI 1330 Å 图(c), 放大 1330 Å图(d)

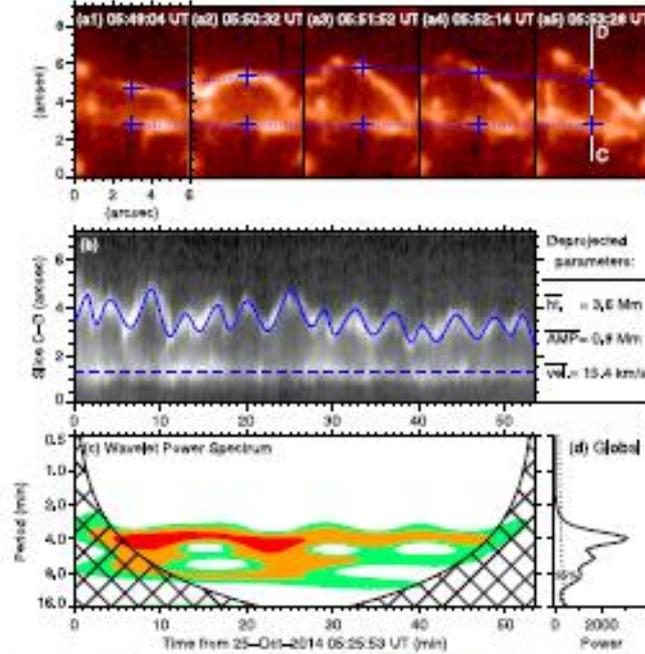


Figure 3. Panels (a1)–(d1): sequence of the 1330 Å images showing the evolution of a section of the light wall. The upper and the lower plus symbols mark the top and base of the wall, respectively, at different times. Panel (b): space-time plot taking slice “C-D” marked in panel (a1). The solid curve delineates the wall top, and the dashed line marks the wall base. Panels (c) and (d): wavelet power spectrum and the global power of the light-wall oscillations.

图 8. 10: 亮墙演化 (a)、空间-时间图 (b)、亮墙的小波功率谱 (c) 及总能量

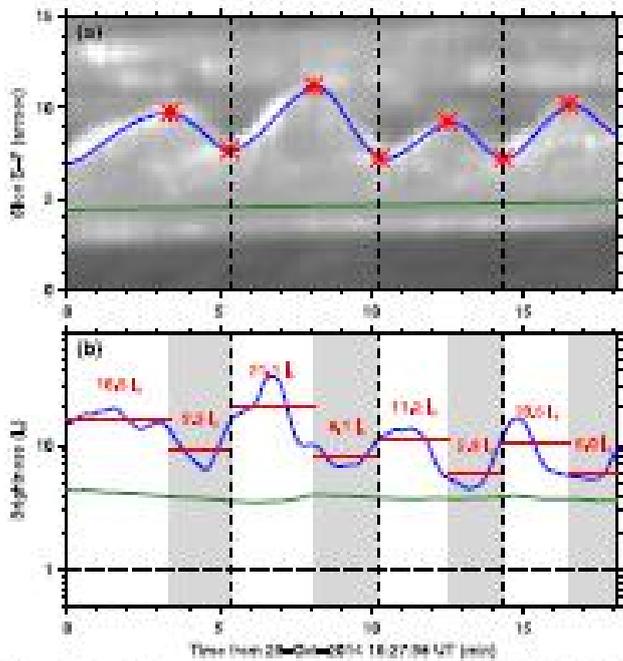


Figure 5. Panel (a): space-time plot derived along slice “E-F” marked in Figure 4(b2). The blue curve outlines the top of the light wall. The red asterisks mark the locations of the maxima and the minima of four periods that are separated by three vertical dashed lines. Panel (b): brightness of the wall top (blue curve) and wall body (green curve) along the blue curve and green line in panel (a). The dotted line is the brightness of the umbra. The white and gray regions mark the upward and downward motion stages, respectively. The red lines associated with the labels indicate the average brightness in different stages.

图 8. 11: 亮墙的空间-时间图 (a), 亮墙亮度

8.2.4. 为什么是富耀斑活动区的贫 CME?

太阳活动区(AR)是两个太阳最剧烈爆发现象的源, 即耀斑与 CME, 在过去 24 年最大的活动区 NOAA 12192 不寻常地产生了一百多个耀斑, 包括 32 个 M 级和 6 个 X 级, 但仅仅产生了一个小 CME。一般认为耀斑与 CME 是相同爆发观测的两个现象, 但这个活动区为何却是富耀斑而贫 CME? Liu 等 (2016, APJ, 826, 119) 比较了这个和其它 4 个活动区: 两个富产, 两个惰性。SDO/HMI 矢量磁场图分析显示, 富耀斑的 AR 12192 与另外两个富产活动区相似比两个惰性 AR 具有较大的磁通量、电流、自由磁能; 与两个富产 AR 相反, 它没有沿中性线的强、集中电流螺度, 说明缺少由高剪切或缠绕的成熟磁场结构。此外, AR 12192 上方的衰变指数相当低。这些结果说明, 富产 AR 总是非常大、具有足够的电流和自由能驱动耀斑, 但耀斑是否伴随 CME 似乎与 (1) 存在成熟的剪切或扭曲核场用作 CME 的种子和 (2) 对磁拱足够弱的限制密切相关。

表 8. 3: 活动区参数信息

NOAA	11157	11158	11428	11429	12192
Hemisphere	North	South	South	North	South
Date on the visible disk	20110208-0217	20110211-0221	20120302-0313	20120303-0315	20141018-1030
Productivity	Inert	Flare-CME-rich	Inert	Flare-CME-rich	Flare-rich only
Φ (10^{22} Mx)	0.55 ± 0.25	1.88 ± 1.09	1.25 ± 0.11	5.58 ± 0.23	15.01 ± 2.06
ρ_{lux} (10^{23} erg cm^{-1})	0.44 ± 0.30	4.97 ± 3.34	2.05 ± 0.78	13.88 ± 2.64	48.65 ± 4.87
I_{total} (10^{13} A)	0.97 ± 0.35	4.08 ± 2.19	2.43 ± 0.35	9.45 ± 1.20	22.28 ± 1.57
\overline{H}_c (10^{-3} G 2 m $^{-1}$)	-4.62 ± 4.69	13.11 ± 9.98	-3.69 ± 4.31	-22.27 ± 4.88	-3.24 ± 1.75
$H_{c\text{total}}$ (10^3 G 2 m $^{-1}$)	0.42 ± 0.17	2.19 ± 1.20	0.98 ± 0.16	4.76 ± 0.81	12.17 ± 0.99

Note. The lower five rows show the mean values and the standard deviations of the quantities during the period in which the CMD was within $\pm 45^\circ$. See Table 3 for the formulas of the parameters.

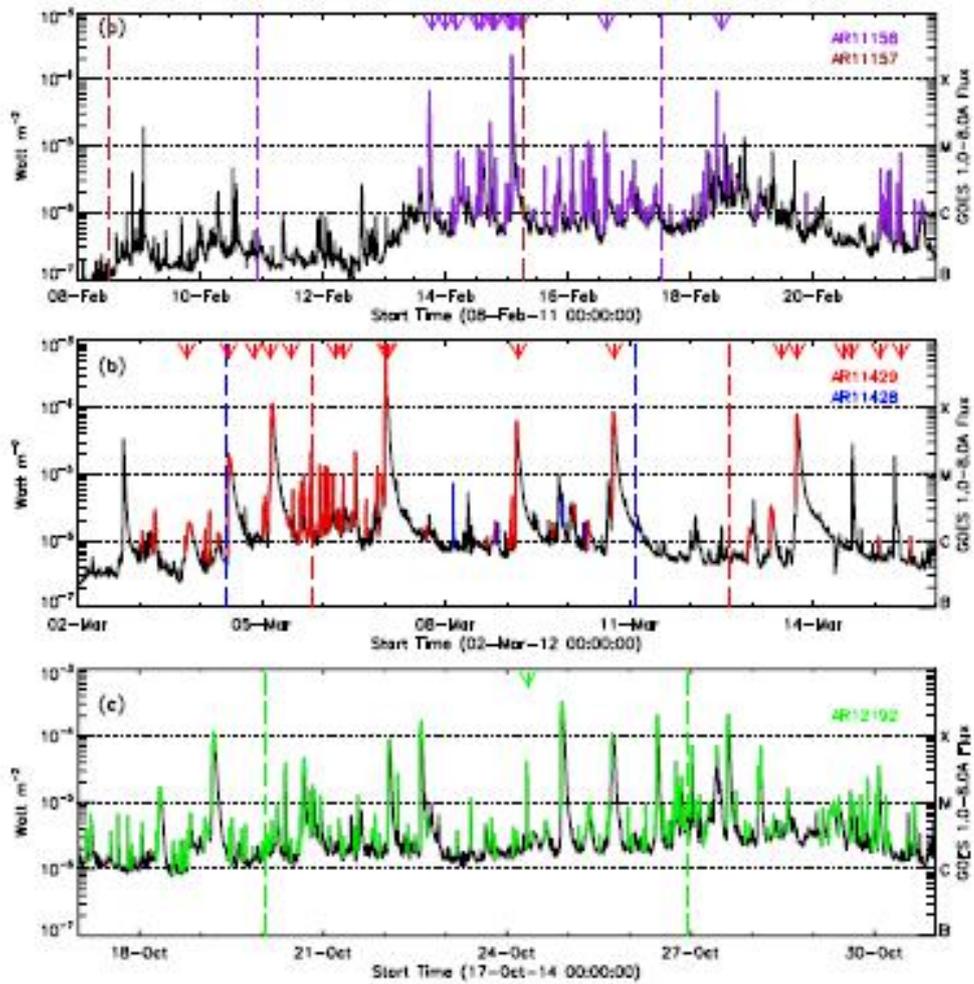


Figure 1. GOES soft X-ray light curves during the Alos' disk passage; panel (a) for ARs 11157 and 11158, (b) for ARs 11428 and 11429, and (c) for AR 12192. Superimposed colored lines indicate the associated flares; brown, purple, blue, red, and green colors represent AR 11157, 11158, 11428, 11429, and 12192, respectively. CMEs originating from the corresponding ARs are marked by arrows. Vertical dashed lines indicate the time window when the central meridian distance (CMD) of the Alos' geometric centers were within $\pm 45^\circ$.

图 8.12: 各活动区的 GOES 流量, 彩色曲线代表耀斑, 箭头表示 CME

表 8. 4: NOAA11158, 11429 和 12192 活动区的耀斑及 CME 参数

Table 2
Flares and CMEs from ARs 11158, 11429, and 12192a

AR No.	No.	Flare				Class	CMEs		
		Date	Begin (UT)	End (UT)	Peak (UT)		Time ^b (UT)	Width (degrees)	Speed (km s ⁻¹)
11158	1	2011/Feb/13	17:28:00	17:47:00	17:38:00	M6.6	18:56:05	276	373
	2	2011/Feb/13	—	—	—	—	2:354:00	73	370 ^c
	3	2011/Feb/14	04:29:00	05:09:00	04:49:00	C8.3	0:424:00	68	384 ^c
	4	2011/Feb/14	11:51:00	12:26:00	12:00:00	C1.7	1:224:00	61	810 ^c
	5	2011/Feb/14	13:47:00	14:42:00	14:27:00	C7.0	1:400:07	22	380
	6	2011/Feb/14	17:20:00	17:52:00	17:26:00	M2.2	1:824:05	360	326
	7	2011/Feb/14	19:23:00	19:36:00	19:30:00	C5.6	1:924:00	81	349 ^c
	8	2011/Feb/15	00:31:00	00:48:00	00:38:00	C2.7	0:054:00	82	1843 ^c
	9	2011/Feb/15	01:44:00	02:06:00	01:56:00	X2.2	0:224:05	360	669
	10	2011/Feb/15	04:27:00	04:37:00	04:32:00	C4.8	0:524:00	104	1740 ^c
	11	2011/Feb/16	01:32:00	01:46:00	01:39:00	M1.0	—	—	—
	12	2011/Feb/16	07:35:00	07:44:00	07:44:00	M1.1	—	—	—
	13	2011/Feb/16	14:19:00	14:29:00	14:25:00	M1.6	1:454:00	75	320 ^c
	14	2011/Feb/18	09:55:00	10:15:00	10:11:00	M6.6	—	—	—
	15	2011/Feb/18	—	—	—	—	1:212:05	89	350
	16	2011/Feb/18	12:59:00	13:06:00	13:03:00	M1.4	—	—	—
11429	1	2012/Mar/03	17:56:00	18:05:00	18:03:00	C1.1	1:856:05	192	1078
	2	2012/Mar/04	10:29:00	12:16:00	10:52:00	M2.0	1:140:07	360	1306
	3	2012/Mar/04	—	—	—	—	2:048:05	50	720
	4	2012/Mar/05	02:30:00	04:43:00	04:05:00	X1.1	0:312:09	92	594
	5	2012/Mar/05	—	—	—	—	1:124:06	50	428
	6	2012/Mar/05	19:10:00	19:21:00	19:16:00	M2.1	—	—	—
	7	2012/Mar/05	19:27:00	19:52:00	19:30:00	M1.8	—	—	—
	8	2012/Mar/05	22:26:00	22:42:00	22:34:00	M1.3	—	—	—
	9	2012/Mar/06	00:22:00	00:31:00	00:28:00	M1.3	—	—	—
	10	2012/Mar/06	01:36:00	01:50:00	01:44:00	M1.2	—	—	—
	11	2012/Mar/06	04:01:00	04:08:00	04:05:00	M1.0	0:448:06	111	536
	12	2012/Mar/06	07:52:00	08:00:00	07:55:00	M1.0	0:812:08	107	599
	13	2012/Mar/06	12:23:00	12:54:00	12:41:00	M2.1	—	—	—
	14	2012/Mar/06	21:04:00	21:14:00	21:11:00	M1.3	—	—	—
	15	2012/Mar/06	22:49:00	23:11:00	22:53:00	M1.0	—	—	—
	16	2012/Mar/07	00:02:00	00:40:00	00:24:00	X5.4	0:024:06	360	2684
	17	2012/Mar/07	01:05:00	01:23:00	01:14:00	X1.3	0:150:24	360	1825
	18	2012/Mar/09	03:22:00	04:18:00	03:53:00	M6.3	0:426:09	360	950
	19	2012/Mar/10	17:15:00	18:30:00	17:46:00	M8.4	1:800:05	88	491
	20	2012/Mar/13	—	—	—	—	1:156:05	54	229
	21	2012/Mar/13	17:12:00	17:41:00	17:30:00	M7.9	1:756:05	360	1884
	22	2012/Mar/14	—	—	—	—	1:156:05	11	565
	23	2012/Mar/14	—	—	—	—	1:448:05	28	533
	24	2012/Mar/15	—	—	—	—	0:200:05	74	318
	25	2012/Mar/15	—	—	—	—	1:024:05	31	388
12192	1	2014/Civ/18	07:02:00	08:49:00	07:58:00	M1.6	—	—	—
	2	2014/Civ/19	04:17:00	05:48:00	05:03:00	X1.1	—	—	—
	3	2014/Civ/20	09:00:00	09:20:00	09:11:00	M3.9	—	—	—
	4	2014/Civ/20	16:00:00	16:55:00	16:37:00	M4.5	—	—	—
	5	2014/Civ/20	18:55:00	19:04:00	19:02:00	M1.4	—	—	—
	6	2014/Civ/20	19:53:00	20:13:00	20:03:00	M1.7	—	—	—
	7	2014/Civ/20	22:43:00	23:13:00	22:55:00	M1.2	—	—	—
	8	2014/Civ/21	13:35:00	13:40:00	13:38:00	M1.2	—	—	—
	9	2014/Civ/22	01:16:00	01:59:00	01:59:00	M6.7	—	—	—
	10	2014/Civ/22	05:11:00	05:21:00	05:17:00	M2.7	—	—	—
	11	2014/Civ/22	14:02:00	14:50:00	14:28:00	X1.6	—	—	—
	12	2014/Civ/23	09:44:00	09:56:00	09:50:00	M1.1	—	—	—
	13	2014/Civ/24	07:37:00	07:53:00	07:48:00	M4.0	0:800:05	96	677
	14	2014/Civ/24	21:07:00	22:13:00	21:40:00	X3.1	—	—	—
	15	2014/Civ/25	16:55:00	17:08:00	17:08:00	X1.0	—	—	—
	16	2014/Civ/26	10:04:00	11:18:00	10:56:00	X2.0	—	—	—
	17	2014/Civ/26	17:08:00	17:30:00	17:17:00	M1.0	—	—	—

Table 2
(Continued)

AR No.	No.	Flare				Class	CMEs		
		Date	Begin (UT)	End (UT)	Peak (UT)		Time ^b (UT)	Width (degrees)	Speed (km s ⁻¹)
	18	2014/Civ/26	18:07:00	18:20:00	18:15:00	M4.2	—	—	—
	19	2014/Civ/26	18:43:00	18:56:00	18:49:00	M1.9	—	—	—
	20	2014/Civ/26	19:59:00	20:45:00	20:21:00	M2.4	—	—	—
	21	2014/Civ/27	00:06:00	00:44:00	00:34:00	M7.1	—	—	—
	22	2014/Civ/27	01:44:00	02:11:00	02:02:00	M1.0	—	—	—
	23	2014/Civ/27	03:35:00	03:46:00	03:41:00	M1.3	—	—	—
	24	2014/Civ/27	09:59:00	10:26:00	10:09:00	M6.7	—	—	—
	25	2014/Civ/27	14:12:00	15:09:00	14:47:00	X2.0	—	—	—
	26	2014/Civ/27	17:33:00	17:47:00	17:40:00	M1.4	—	—	—
	27	2014/Civ/28	02:15:00	03:08:00	02:41:00	M3.4	—	—	—
	28	2014/Civ/28	03:23:00	03:41:00	03:32:00	M6.6	—	—	—
	29	2014/Civ/28	13:54:00	14:23:00	14:06:00	M1.6	—	—	—
	30	2014/Civ/29	06:03:00	06:20:00	06:20:00	M1.0	—	—	—
	31	2014/Civ/29	09:54:00	10:06:00	10:01:00	M1.2	—	—	—
	32	2014/Civ/29	14:24:00	14:33:00	14:33:00	M1.4	—	—	—
	33	2014/Civ/29	16:06:00	16:33:00	16:20:00	M1.0	—	—	—
	34	2014/Civ/29	18:47:00	18:52:00	18:50:00	M1.3	—	—	—
	35	2014/Civ/29	21:18:00	21:25:00	21:22:00	M2.3	—	—	—
	36	2014/Civ/30	00:34:00	00:40:00	00:37:00	M1.3	—	—	—
	37	2014/Civ/30	01:19:00	01:56:00	01:35:00	M3.5	—	—	—
	38	2014/Civ/30	04:17:00	04:36:00	04:26:00	M1.2	—	—	—

Notes.
^a Blank in the flare (CME) column mean that no C-class or more intense flare (CME) is associated with the CME (flare).
^b First appearance in the field of view of the SDO/LASCO C2 or the STEREO/COR2 (missed by C2).
^c CMEs recorded by COR2.

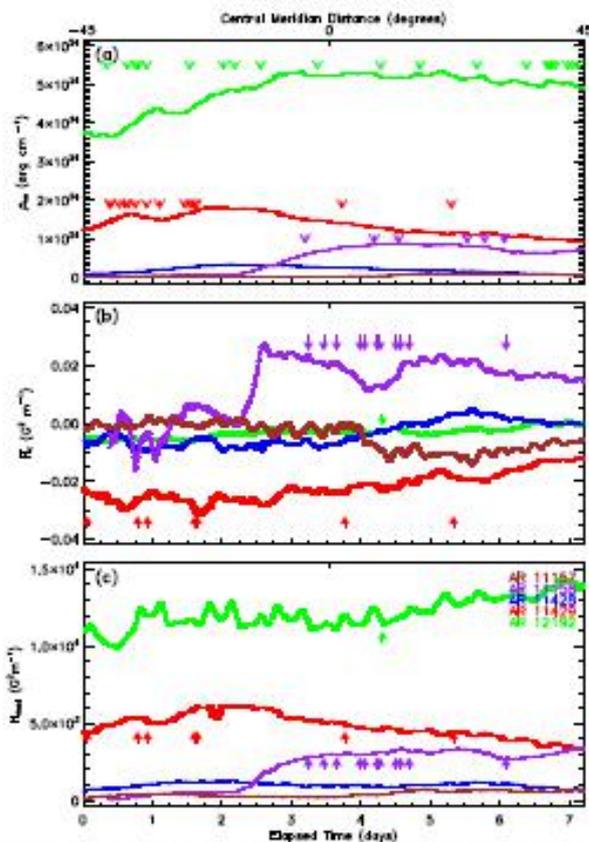


Figure 2. The evolution of proxy of photosphere free magnetic energy W_{free} (in panel (a)), mean current helicity \overline{H}_c (in panel (b)), and total unsigned current helicity H_{total} (in panel (c)); the bold arrows in panel (a) indicate associated flares more severe than M-class; the solid arrows in panel (b) and (c) are for CMEs; the brown, purple, blue, red, and green colors are for AR 11157, 11158, 11428, 11429, and 12192, respectively.

图 8. 13: 各活动区的自由磁能 (a)、平均电流螺度(b)及总无符号电流螺度箭头表示 CME

8.2.5. 与耀斑相随的 CME 中爆炸喷射触发

李晓红等 (2015, ApJL, 814, L13)利用 SDO 数据分析了 NOAA 12192 活动区的唯一一次耀斑(M4.0 级)伴随 CME 事件, 暗条的爆发引起了 blow-out 的 jet, 从而导致发生 M4.0 耀斑。该耀斑位于活动区的边缘而不是核心区, 耀斑靠近明显的开放线, 在 EUV 以扇形迅速扩张, 在耀斑物质与开放线的相互作用下, 耀斑变成了爆发耀斑从而导致 CME。在第一个爆发相同的爆发地点, 另一个暗条爆发。利用抚仙湖太阳观测站的高空间及时间分辨率 $H\alpha$ 数据和新真空太阳望远镜数据 (NVST), 研究了第二个暗条与附近开放线的相关作用, 暗条与开放线的重联构成了一新系统, 由于暗条的松解运动, 新系统转动, 说明 twist 从闭合暗条系统转移到开发系统, 此外, twist 似乎从低层传播到高层大气, 最终被 CME 带到行星际空间。

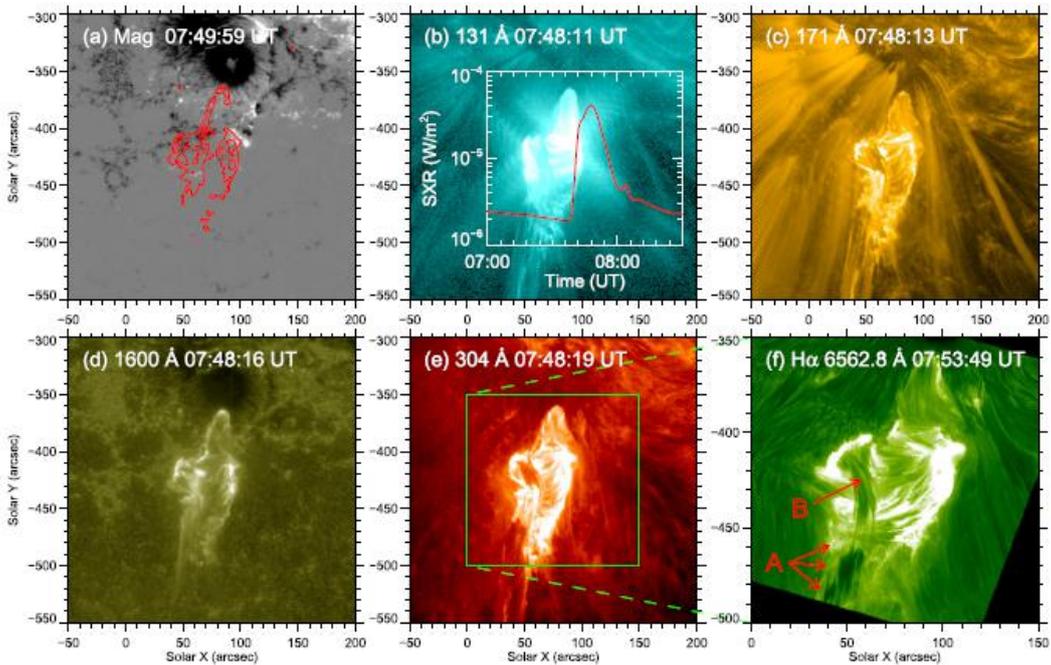


Figure 1. HMI LOS magnetogram (panel (a)), AIA multi-wavelength images (panels (b)–(e)), and NVST H α image (panel (f)) displaying the appearance of the first eruption. The red contours in panel (a) display the flare ribbons in 1600 Å. In panel (b), the red curve displays the variation of the GOES soft-X-ray flux. The green square in panel (e) outlines the FOV of panel (f). Arrows “A” and “B” in panel (f) denote the jet and the filament, respectively.

图 8. 14: HMI LOS 磁图 (a), AIA 多波段图 ((b) - (e)) 及 NVST H α 图 (f)

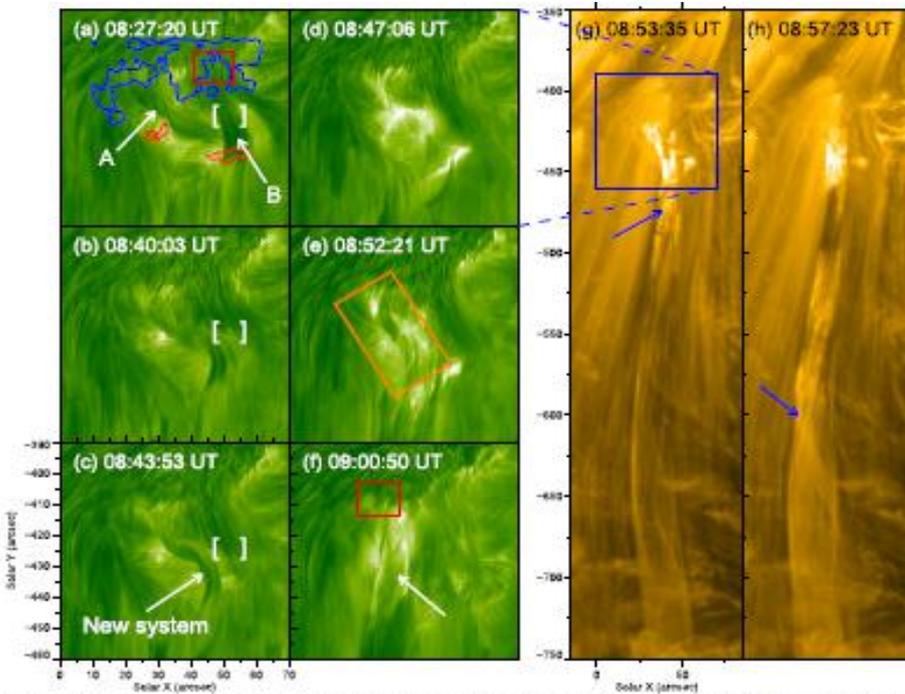


Figure 4. Panels (a)–(f): NVST H α images showing the detailed interaction process of the filament and the “open” line (also see Figure 3’s animation (b)). Panels (g)–(h): AIA 171 Å images displaying the outward propagation process of the magnetic twist (also see Figure 4’s animation). The red and blue curves in panel (a) are the contours of the positive and negative magnetic fields, respectively. Arrows “A” and “B” in panel (a) denote the filament and the “open” line, respectively. The arrow in panel (c) indicates the new system, and the arrow in panel (f) denotes the structure of the system after rotation. The brackets in panels (a)–(c) mark the area where the “open” field lines clean reconnected. The red rectangles in panels (a) and (f) outline the footpoints of the “open” line. The brown rectangle in panel (a) outlines the FOV of Figure 3. The arrows in panels (g) and (h) indicate the positions of the outward propagating twist. (An animation of this figure is available.)

图 8. 15: (a) - (f): NVST H α 图显示暗条与开放线的相互作用过程, (g) - (h): AIA 171 Å 图显示磁 twist 向外的传播过程

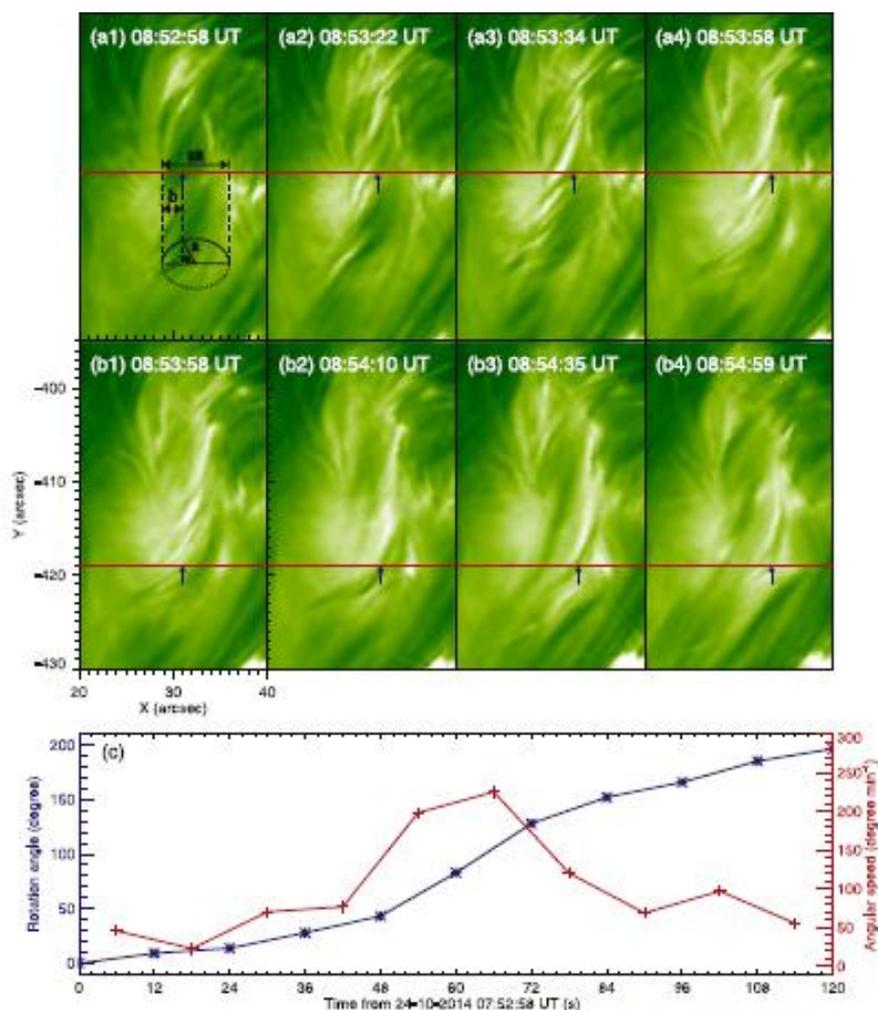


图 8. 16: NVST H α 图像显示的暗条旋转 (a,b), 暗条的转动角度与角速度 (c)

8.2.6. NOAA 12192 活动区大限制耀斑是如何发生的

江朝伟等 (2016, APJ, 828, 62) 用数值驱动 MHD 方法分析了 NOAA12192 活动区大 X 耀斑的物理机制, 在两天时间内, 日冕场被光球场慢慢拉紧, 逐渐产生一大规模日冕电流片, 电流片逐渐上升变薄, 在剪切磁场拱之间建立 ether-cutting 重联, 导致耀斑。模型成功地再现了耀斑的宏观磁场过程, 重联的结果是剪切拱而不是新形成的通量绳, 与其它多数 X 耀斑相比, 发现该耀斑的磁场爆发效应非常弱。

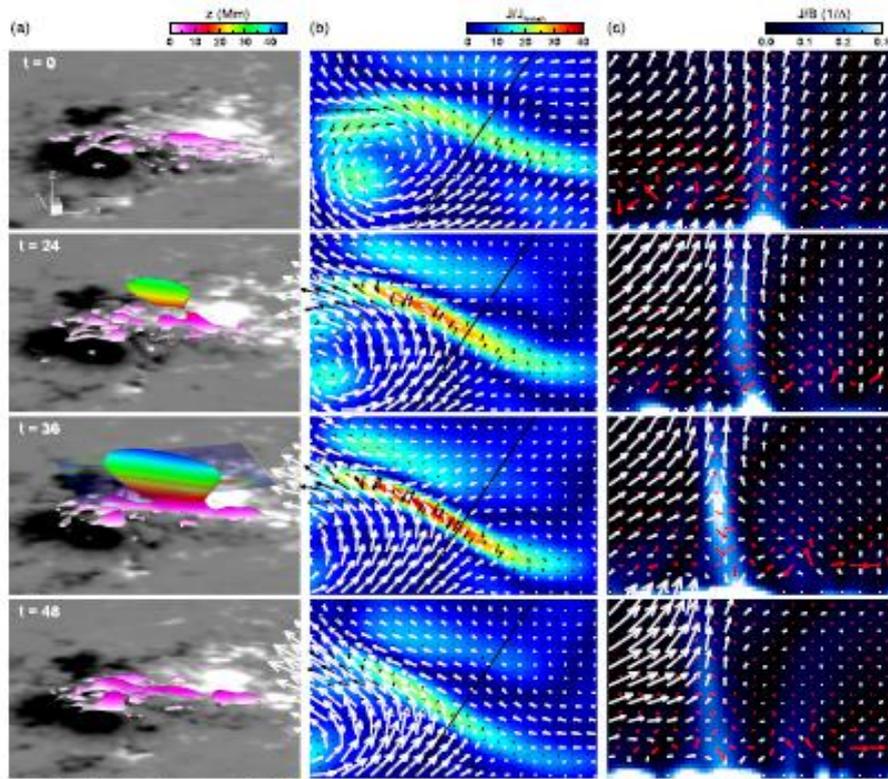


Figure 4. Evolution of the electric current in the MHD model. (a) 3D shape of the CS (defined in the text) at four different times from the beginning to the end of the simulation. The color denotes the height from the bottom surface, which is shown by the photosphere B_p map. (b) A horizontal slice of the volume at $z = 20$ Mm. Its position is indicated by the transparent image shown in $z = 36$ of (a). The color shows electric current density J (scaled by the average value J_{avg} at $z = 0$), and the arrows show plasma velocity vectors (white arrows) as well as the Lorentz force vector (black arrows). The time is the same as (a) from top to bottom. (c) A vertical slice whose horizontal location is denoted by the black inclined line in (b). Vertically, it extends from the bottom to $z = 57$ Mm. The color shows the value of J/B and the arrows represent the velocity (white) and Lorentz force (red). Note that in (b) and (c) each pixel represents a computational grid. (An animation of this figure is available.)

图 8. 17: 模型电流片演化

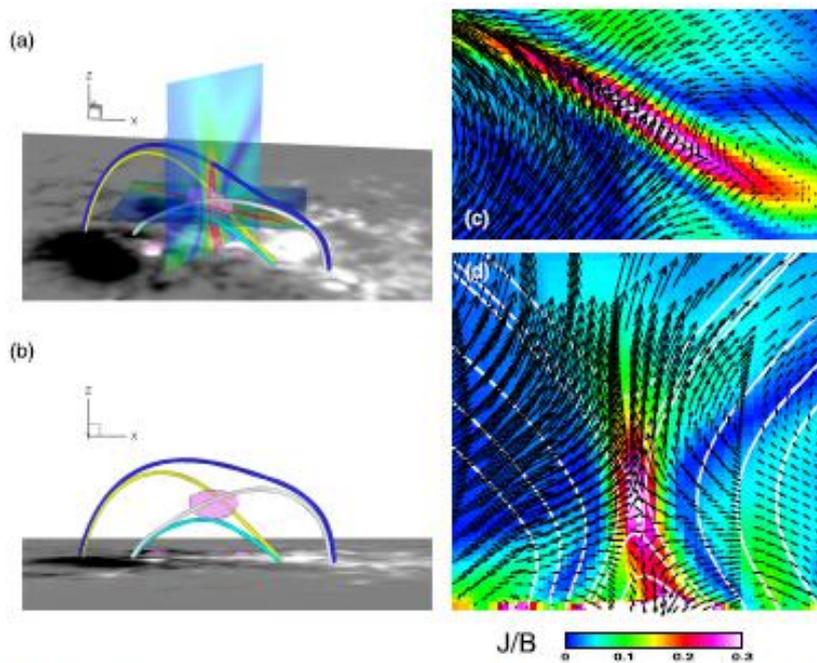


Figure 6. Illustration of the tether-cutting reconnection process in the model. (a) Sampled field lines and horizontal and vertical cross-sections of the reconnection site. The white and yellow curves represent the “before” flare field lines and blue and cyan curves show the new reconnected field lines. The post-reconnection area shows the top-surface of $J/B = 0.3 I/Ax$, which is sandwiched between the pre-reconnection field lines at their crossing point. (b) Side view of the sampled field lines. (c), (d) The horizontal and vertical cross-sections zoomed in to show details of the J/B (in unit of I/Ax) structure and plasma flow vectors. The vertical axis in (c) is r in the range of [0, 92] Mm. The white curves in (c) are 2D field projections of the field lines mapped on the slice.

图 8. 18: tether-cutting 重联模型

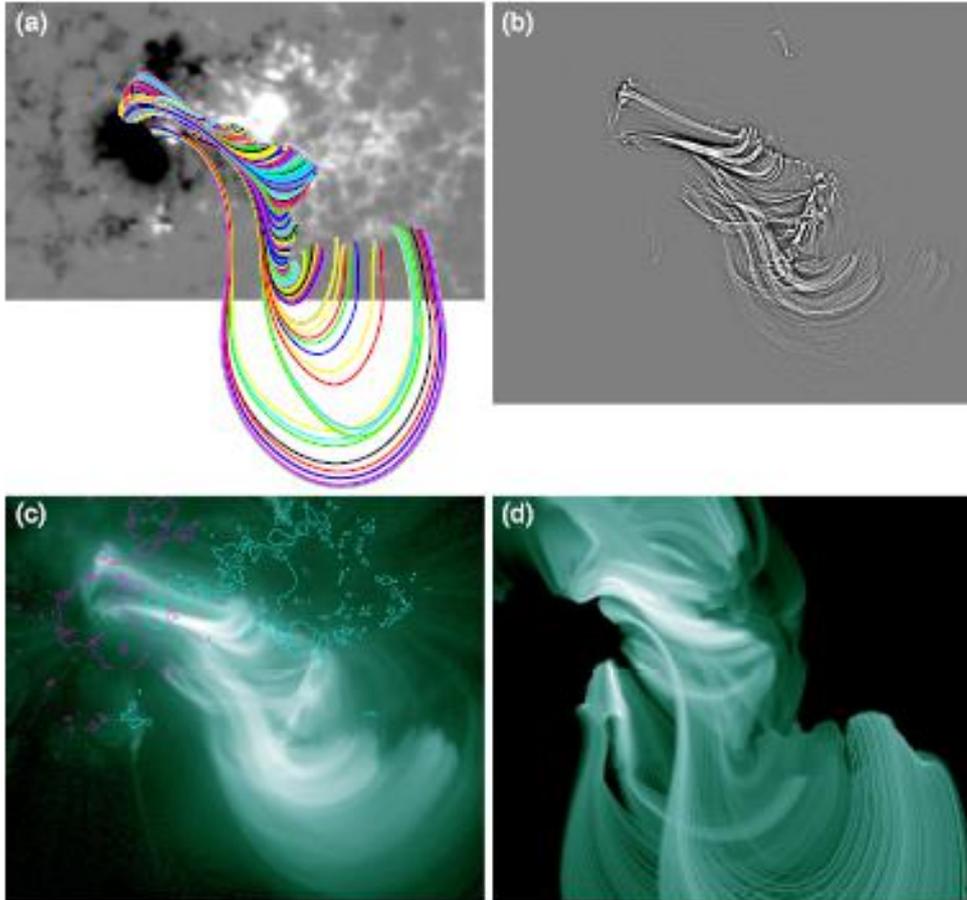


Figure 9. Comparison of the reconnecting field lines from the model with the observed flaring loops. (a) The reconnecting field lines (modeling time at $t = 40$). They are shown with different colors for better discrimination of each field lines. (b) High-pass filtered AIA 94 Å image highlighting the flaring hot loops. (c) Original AIA 94 Å image. Overlaid contours represent photospheric B_z of ± 1000 G. (d) A Synthetic EUV image of the flaring loops based on the modeled magnetic field and current. (specified in the text).

图 8. 19: 模型重构场(a)与观测比较: (b)AIA 滤波像, (c) AIA 像, (d) EUV 像

8.2.7. 由非热电子直接产生的白光耀斑的 IRIS, Hinode, SDO, 和 RHESSI 观测

Lee 等 (2017, APJ, 836,150) 用 IRIS, Hinode, SDO, 和 RHESSI 等数据分析了 2014 年 10 月 22 日 14:02 UT 发生在 NOAA12192 活动区的 X1.6 耀斑, 亮核产生了白光 (WL) 耀斑, 测量了色球及日冕亮核中等离子特性的时间变化, 当发生辐射时, 即使在更热的谱线强度增强相当弱, 还是能观测到爆发蒸发, 时间相关性显示白光辐射是由加速的电子产生, 比较估计的能量, 连续谱增强是由非热电子直接产生。

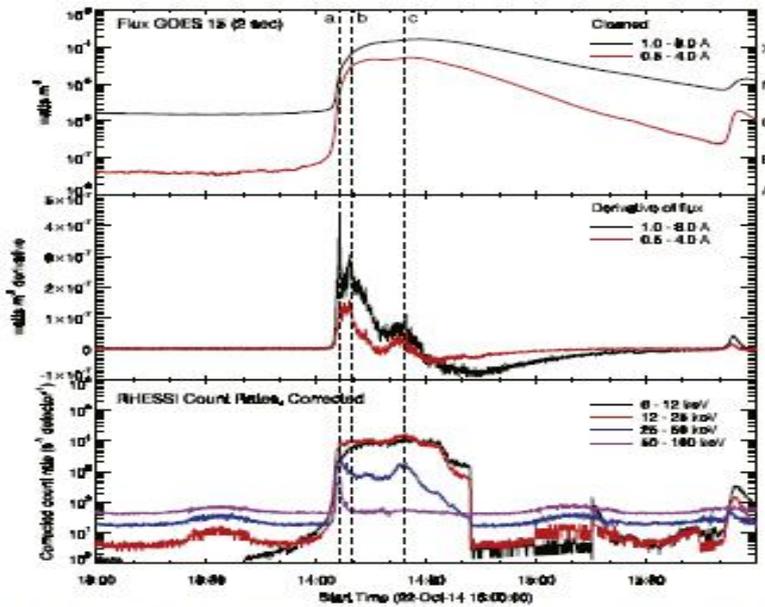


Figure 1. *GOES* X-ray light curve (top) of the X1.6 flare on 2014 October 22 14:06 UT and its time derivative (middle). The *RHESSI* count rates for the different energy bands are plotted in the bottom panel. The vertical dashed lines (a-c) mark the times of the three peaks in the time derivative of the *GOES* X-ray light curve.

图 8. 20: 2014 年 10 月 22 日 14:06 UT X1.6 耀斑的 *GOES* X 射线光变曲线 (上)、时间变化率 (中) 及 *RHESSI* 计数率

表 8. 5: 用到的谱线

Table 1
List of the Spectral Lines Used in the Present Study

Instrument	Line ID (\AA)	$\log(T_{\text{max}}/\text{K})$	
EIS	He II 256.32	4.9	
	O V 248.46	5.4	
	Fe X 184.54	6.1	
	Fe XII 195.12	6.2	
	Fe XIV 264.79 *	6.3	
	Fe XIV 274.20 *	6.3	
	Fe XV 284.16	6.4	
	Fe XVI 263.00	6.8	
	Fe XXIII 263.77	7.2	
	Fe XXIV 192.03	7.2	
	IRIS	O I 1355.6	4.5
		Si IV 1402.8	4.9
		Fe XXI 1354.1	7.1
		Mg II 2798.8	4.0
O IV 1399.77 *		5.2	
O IV 1401.16 *		5.2	

Note. The peak formation temperatures of the spectral lines are taken from the CHIANTI database version 7.0. Lines used for the density determination are marked with asterisks.

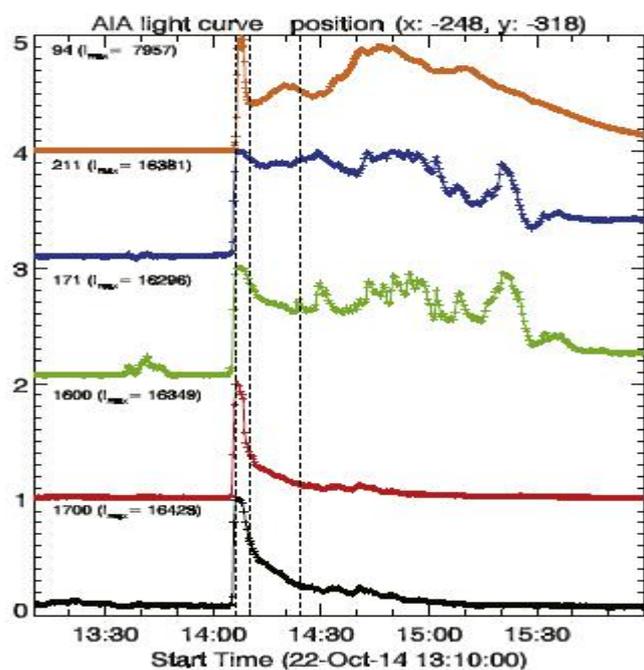


Figure 5. SDO/AIA light curves for the bright kernel. Intensities are normalized by the maximum intensity during the flare observation. The dashed vertical lines correspond to the same times marked in Figure 1.

图 8. 21: 亮核的 SDO/AIA 光变曲线

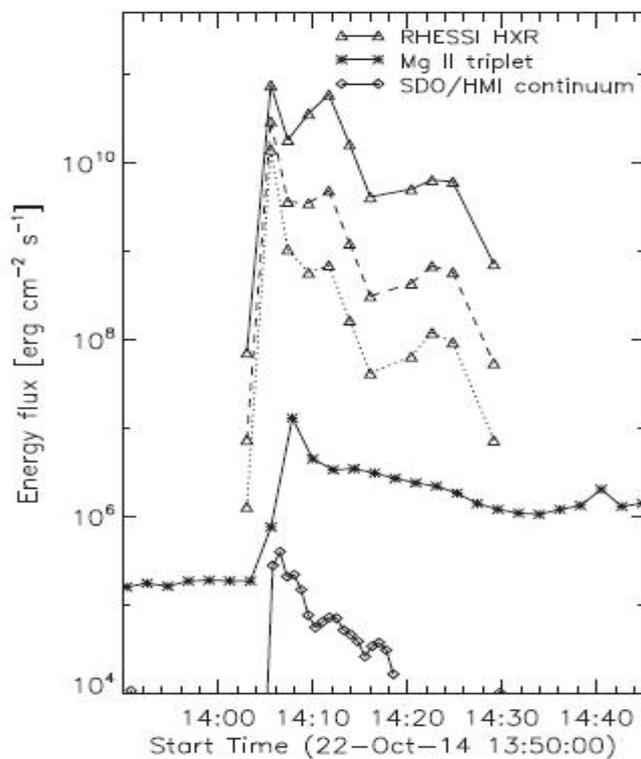


Figure 15. The energy flux of the bright kernel during the flare impulsive phase estimated from the *RHESSI* HXR emission with different threshold energies of 30 keV (solid line), 40 keV (dashed line), and 50 keV (dotted line), the Mg II triplet intensity observed by IRIS, and the WL continuum emission from *SDO/HMI*.

图 8. 22: 脉冲相期间亮核的能量通量

8.2.8. 一个限制 X 耀斑的磁重联率及能量释放

Veronig 和 Polanec (2015, Solar Phys, 290, 2923 - 2942) 用 SDO/AIA、Kanzelhöhe 观测站的 $H\alpha$ 和 $Ca II K$ 滤波像计算磁重联率和重联通量, 分析了 2014 年 10 月 22 日 NOAA12192 活动区限制耀斑 X1.6 的能量释放过程, 从三种数据得出的磁重联率与 RHESSI 观测到的硬 X 射线时间轮廓很像, 总磁重联通量大概占总无极性通量的 2-4%。在双对数空间, 从 27 个爆发事件得出的磁重联通量与 GOES 级别的相关系数为 0.8 左右, 限制 X1.6 耀斑很好地落在爆发耀斑的分布上。该事件显示耀斑带存在一个较大的起始分离, 但耀斑期间没有运动分离。发现耀斑开始前耀斑带结构存在增强辐射, 及连接这些结构的热环。这些观测与通量浮现模型一致, 其中新浮现的小通量管与早期存在的大冕环重联。

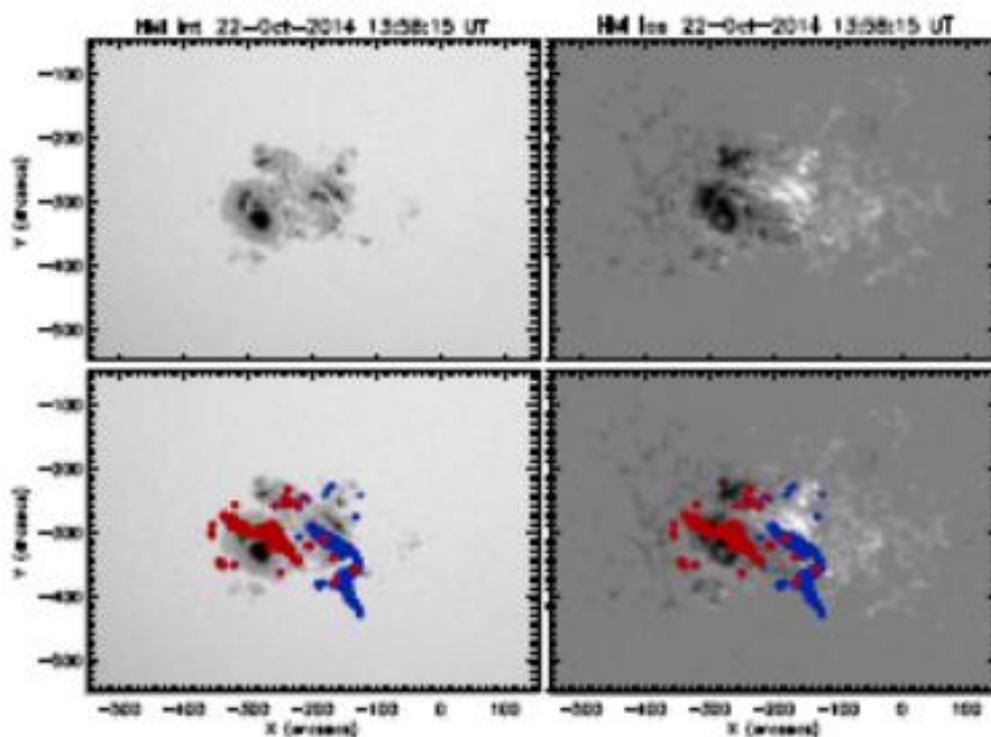


Figure 3 Overview of AR 12192 just before the start of the X1.6 flare on 22 October 2014. Top left: SDO/HMI continuum image, top right: SDO/HMI LOS magnetic-field map scaled to ± 1500 G. (The deficient magnetic-field measurements in the umbra of the strong negative sunspot is an instrumental artifact.) In the bottom panels the same images are shown together with the total flare area determined. Blue denotes flare pixels in positive magnetic polarity regions, red denotes negative polarity.

图 8. 23: AR 12192 X1.6 耀斑之前 SDO/HMI 连续谱 (左) 和 SDO/HMI 视向磁场, 总的耀斑面积标在下图中

Figure 6: Reconnection rates derived from SDO/AIA 1600 Å observations. From top to bottom: evolution of the newly brightened flare area, mean magnetic-field strength in the newly brightened flare pixels, reconnected magnetic flux [$\phi(t)$], magnetic-reconnection rate [$\dot{\phi}(t)$] (blue indicates positive, red negative polarity), and the GOES 1–8 Å soft X-ray flux (black) together with its time derivative (green).

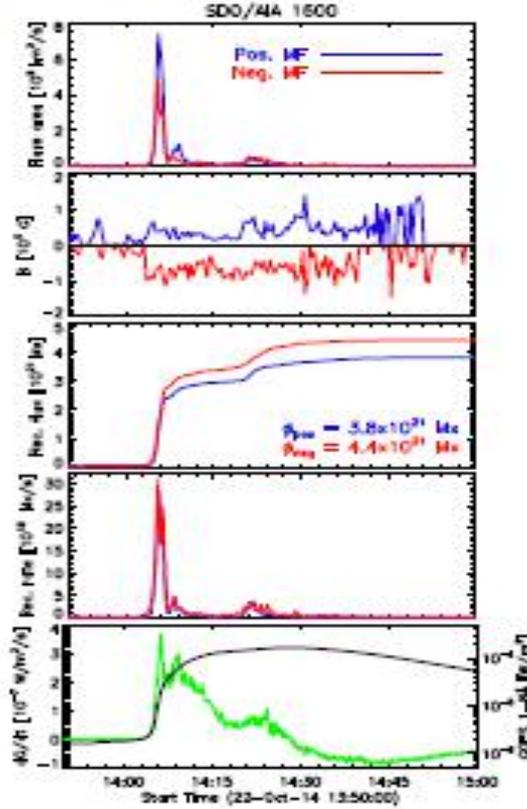


图 8. 24: SDO/AIA 1600 Å磁重联率。从上到下: 新亮耀斑面积、新亮耀斑平均磁场强度、重联磁通量、磁重联率、及 GOES 流量图

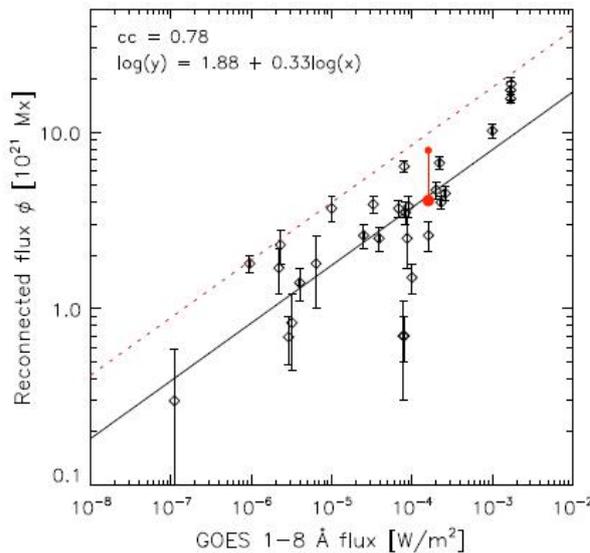


Figure 10 Total flare magnetic-reconnection flux against GOES X-ray class for 27 eruptive flares (black diamonds) and the confined X1.6 flare of 22 October 2014 studied in this article (large red circle; the small red circle denotes an upper estimate). The values for the eruptive flares are from the studies of Qiu and Yurchyshyn (2005), Qiu *et al.* (2007), Miklenic, Veronig, and Vršnak (2009), Hu *et al.* (2014). Note that for the extreme X17 flare of 28 October 2003 we plotted the values derived from three different studies. The full line denotes the linear regression derived in double-logarithmic space, the numbers are shown in the inset. The dotted line marks an *ad-hoc* upper limit to the relation plotted.

图 8. 25: 27 个爆发耀斑总耀斑重联通量-GOES 流量关系图, 限制 X1.6 耀斑 (红圆)

8.2.9. NOAA12192 活动区的同源 Jet 驱动的 CME

Panesar 等 (2016, APJL, 822, L23) 报道了由搭载在 SDO 及 SOHO 卫星上的仪器观测到的同源日冕 Jet 及其 CME, Jet 起源于 NOAA 12192 大活动区的南边缘处的磁浮现与对消地方, 这个活动区在其内部产生了许多非 Jet 大耀斑爆发 (X 及 M 级), 但并无伴随 CME。10 月 20 到 27 日之间, 与内部大耀斑爆发相比, 来自边缘的六个同源 Jet 形成了 CME。与多数 CME 相比, 每个 Jet 驱动的 CME 运动的都比较慢 (~200 - 300 km/s), 其角宽度 (20° - 50°) 与跨过活动区冕流底相当且需喷流变化, 而原先存在的流瞬时膨胀但没被 CME 的通过破坏。在产生 CME 的 Jet 的过渡区等离子体大多数逃离了太阳, 而非产生 CME 的 Jet 的过渡区等离子体大多数返回到太阳表面, CME-Jet 比 CME-Jet 往往比较快且持续时间较长。观测显示每个 Jet 和 CME 都是由扭曲场的开放重联导致的, 扭曲场从 Jet 底爆发, 而爆发场并没有像原先看到的喷流 CME 变成等离子体团, 相反, 喷流指引的冕流底环被重联环的 twist 吹走。

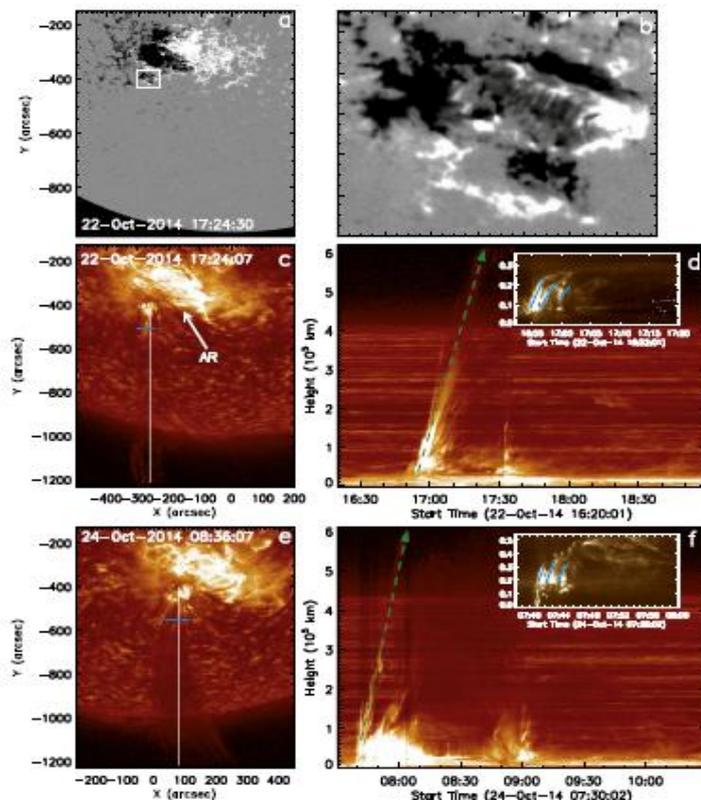


Figure 3. Jet outflow and jet: (a) HMI line-of-sight magnetogram of AR 12192; (b) The jet-producing region (white box of (a)); (c) AIA 304 Å intensity image of jet J2, and (e) jet J5 of Table 1. The white lines in (c) and (e) mark the positions of the time-distance plots in (d) and (f), respectively. Panels (d) and (f) show AIA 304 Å intensity height-time series images along the vertical lines in panel (c) and (e), respectively. Lines in (d) and (f) show the 193 Å intensity time-series images along the blue lines in panel (g) and (h), respectively. They show changes consistent with jet twisting with time. The green dashed arrows in (d) and (f) are the paths used to calculate outflow speeds of the plasma. The x-axis of (a) is the same as (c). (An animation (c) of this figure is available.)

图 8. 26: Jet 外流与自转

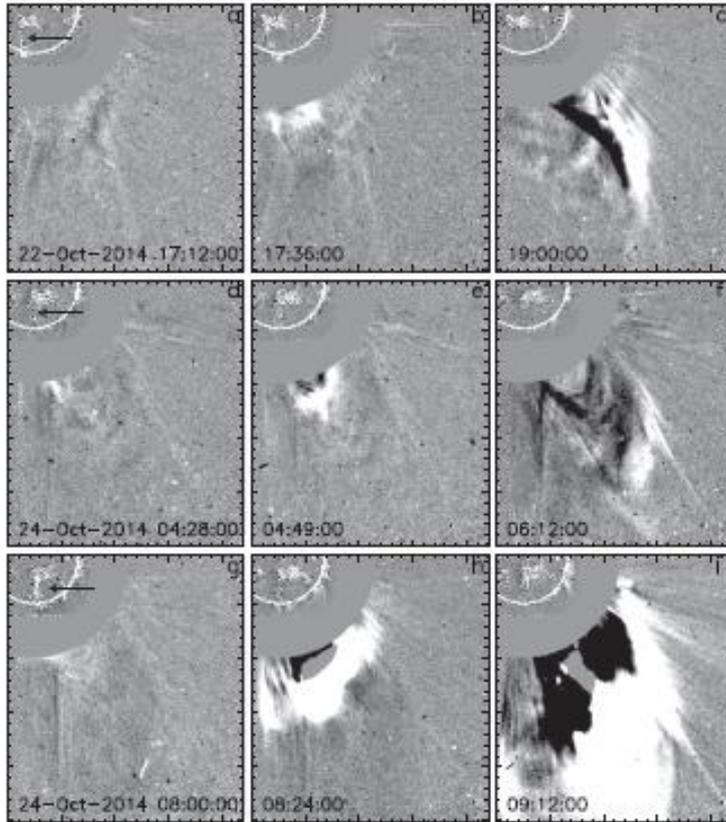


Figure 2. Progression of CMEs: (a)–(c), (d)–(f), and (g)–(i) are LASC0 C2 coronagraph images respectively showing the streamer-puff CMEs from jets J2, J4, and J5. In each frame, an SD0/AIA 193 Å running-difference image is co-aligned with the C2 image. The outer edge of the AIA solar disk is outlined in white in each frame. The black arrows in (a), (d), and (g) point to the J2, J4, and J5 jets, respectively. (An animation (a–i) of this figure is available.)

图 8. 27: LASC0 C2 差分图, 显示从 Jet J2、J4 和 J5 喷出的 streamer-puff CME

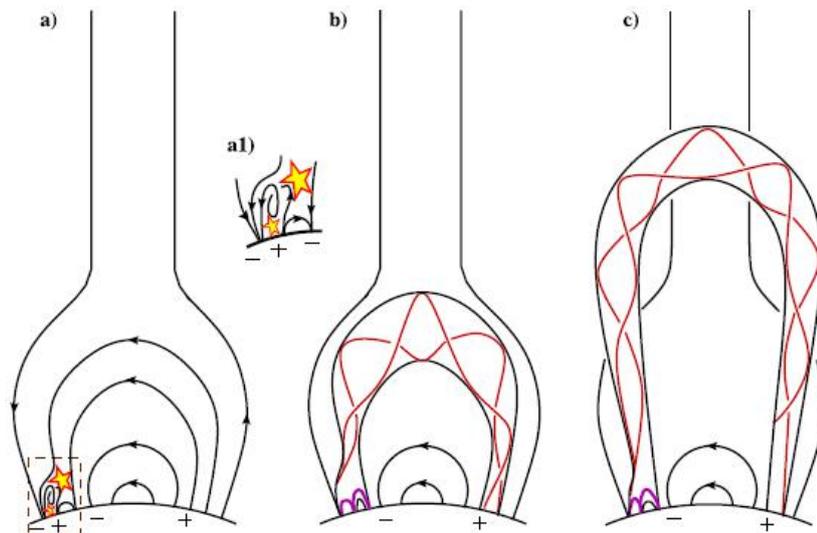


Figure 4. Schematic interpretation of the observations based on HMI, AIA, and LASC0 images. These drawings depict the AR forming the helmet arcade below the streamer, viewed on the limb from the south. The helical black line in (a) represents twisted magnetic field in the jet base before and early during jet eruption. The stars show the locations where reconnection is taking place. Inset (a1) shows a zoomed-in view of the brown-boxed region of (a). The thick low magenta loops in (b) and (c) represent flare loops that result from internal (left) and external (right) reconnection of the erupting twisted field. (Complex flare loops at the jets' base in Figure 1 would correspond to the low-lying magenta loops of (b) and (c).) The red lines in (b) and (c) represent the twist transferred from the erupting field to the high-reaching jet-guiding coronal loop of the streamer-base helmet arcade by the external reconnection. The "+" and "-" labels are for positive and negative magnetic polarity, respectively.

图 8. 28: 基于 HMI, AIA 及 LASC0 观测解释示意图

8.2.10. NOAA12192 活动区三带耀斑的触发过程

Bamba 等 (2017, APJ, 838, 134) 利用 Hinode/SOT 及 SDO/HMI 和 AIA 数据, 通过分析磁场结构的空-时相关性, 特别是水平场的非势性及太阳大气的亮结构, 研究了 NOAA12192 活动区三带耀斑的触发过程, 发现正极性的西侧通过侵入负极区成为耀斑触发的地方, 这是由于该区剪切场的符号与活动区的大剪切相反, 耀斑爆发前明显的增亮是在极性翻转线 (PIL) 上观测到的, 这与最近提出的耀斑触发模型一致, 该模型提示小的反向剪切 (RS) 磁场扰动可能触发太阳耀斑。他们还发现 RS 区域偏离 PIL, 与理论预测相反。

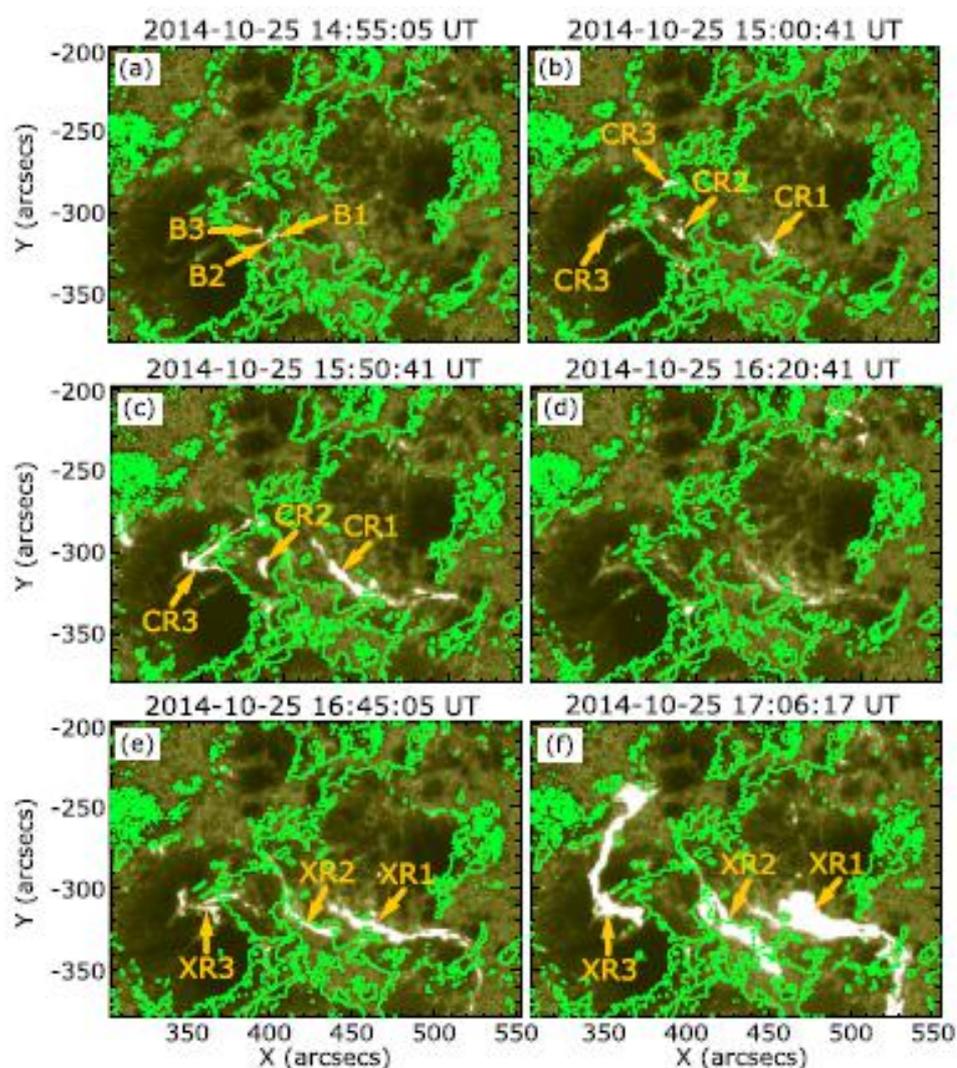


Figure 2. Temporal evolution of the significant brightenings in the upper photosphere and transition region, and the flare ribbons in AIA 1600 Å images. Green lines indicate the PILs in the HMI LOS magnetograms at each time. The intensity scale ranges in 0–2000 DN. (a) Small brightenings are intermittently seen at the west side of the IPF as indicated by the yellow arrows. (b) The three ribbons (CR1–CR3) of the C5.1 flare. (c) The three ribbons (CR1–CR3) of the C9.7 flare. (d) A faint ribbon-like brightening remains at the region where CR1 is seen. (e) The initial three ribbons of the X1.0 flare. XR1 is the positive ribbon, and XR2 and XR3 are the negative ribbons. (f) Enhanced three-ribbon emission of the X1.0 flare.

图 8.29: 在光球上方及过度区亮斑演化和 AIA 1600 Å 图中的耀斑带

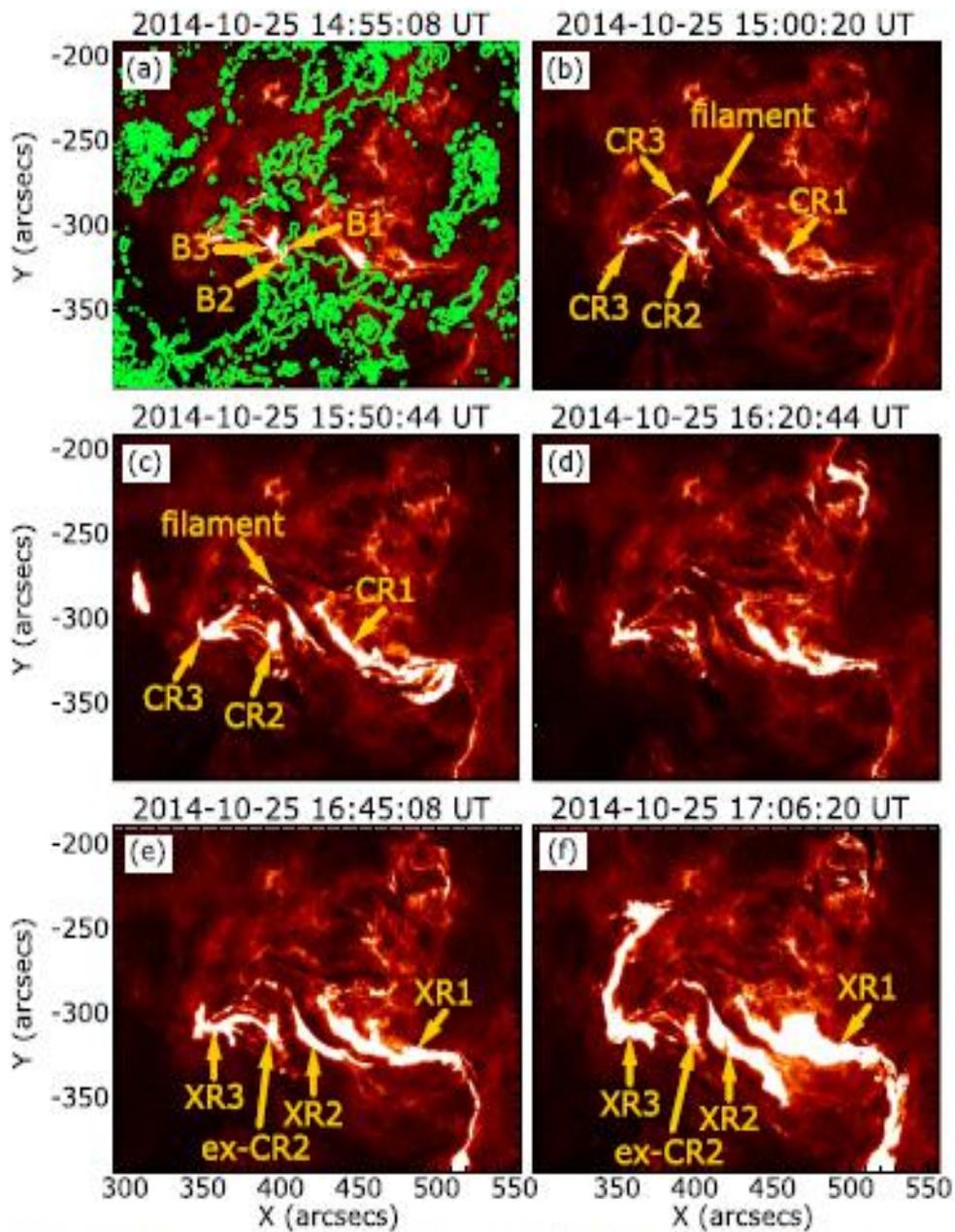


Figure 4. Temporal evolution of the chromospheric brightenings and flux ribbons in AIA 304 Å images. The FLEs are overlaid with green lines in panel (a). The intensity scale range is 0–1000 DN. Panels (a)–(f) show almost the same features as Figure 2, but the brightening B1 and B2 are connected to each other via a small loop striding over the local FLE at the west side of the ST. Moreover, the CR1 ribbon here remains clearer than that seen in Figure 2(c), and CR3 also remains in panel (d).

图 8.30: AIA 304 Å 观测到的色球亮斑

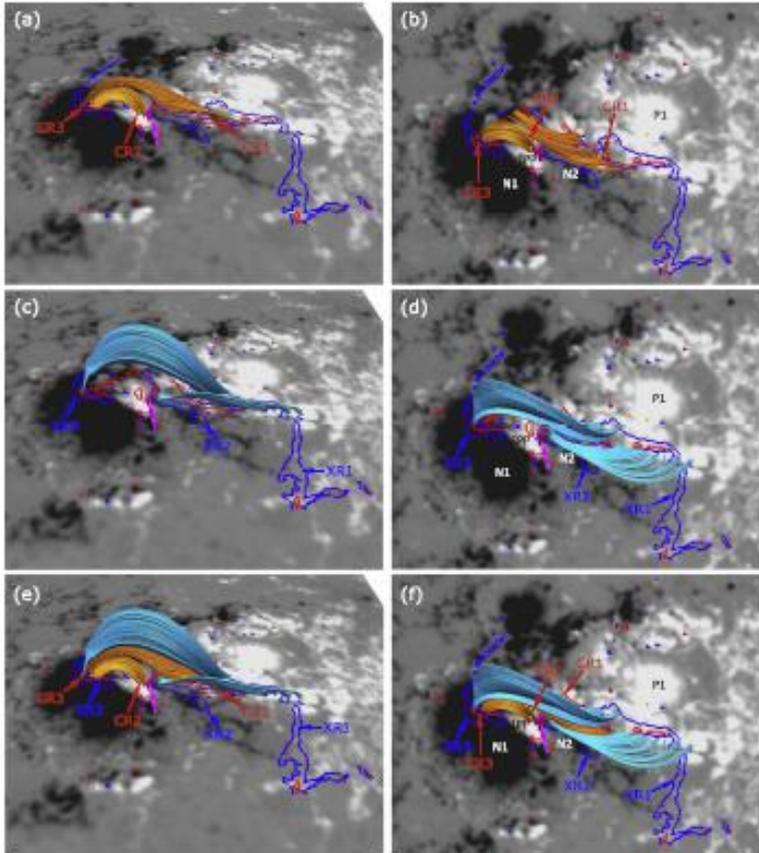


Figure 10. Magnetic field lines extrapolated using the NLFFF method. The left/right columns show a bird's eye view/top view of the same image. The grayscale images are the SDO LGS magnetograms taken on October 28, 15:00 UT. The red/blue contour outline is the brightenings (700 DN) in AIA 1600 Å such as the flare ribbons on 15:50 UT/1745 UT. The small magenta tubes indicated by the magenta arrows are the local magnetic field lines at the west side of the IFV. The orange/sky-blue tubes indicate the coronal magnetic field lines anchored in the flare ribbons of the C9.7/X1.0 flare in panels (a) and (b)/(c) and (d), respectively. All the coronal magnetic field lines are plotted in panels (e) and (f).

图 8. 31: 非线性无力场磁场外推磁力线

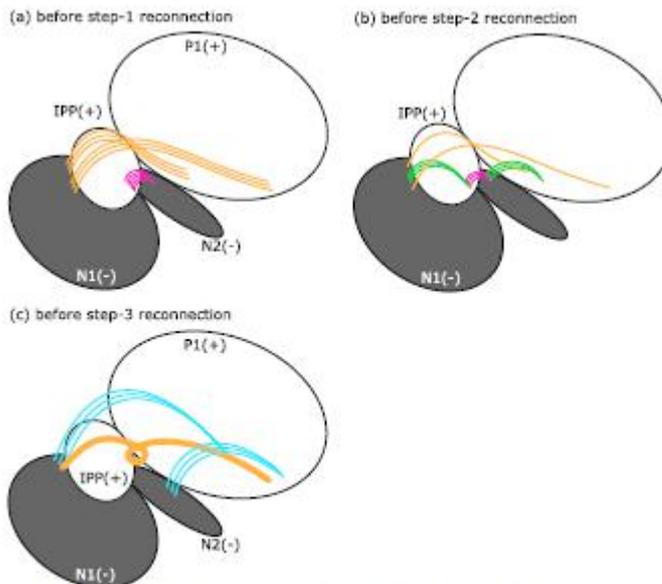


Figure 11. Schematics of the magnetic field lines before step-1, step-2, and step-3 reconnection. White/gray indicate the positive/negative polarity of the LGS magnetic field. (a) Before step-1 reconnection. The orange and magenta loops illustrate the P1-N1 and IPP-N2 loops in Figure 10 (a) and (b). (b) Before step-2 reconnection (i.e., after step-1 reconnection). The orange and magenta loops are the same as those in panel (a). The green loops indicate the small loops connecting IPP-N1 and P1-N2, which are formed by the flux cancellation between the orange and magenta loops. (c) Before step-3 reconnection. The sky-blue loops are equivalent to the P1-N2 and P1-N1 loops in Figure 10 (c) and (d). The thick orange line illustrates the flux rope that is formed by step-2 reconnection under the sky-blue loops.

图 8. 32: 重联示意图

8.2.11.2014年10月24日 X3.1 限制耀斑与2011年2月15日 X2.2 爆发耀斑的比较

Jing 等 (2015, RAA, 15, 1537 - 1546) 从自由能、相对磁螺度和衰变指数角度比较了发生 NOAA 11158 活动区伴随全晕 CME 的 X2.2 爆发耀斑与 12192 活动区没有 CME 的限制耀斑, 两个耀斑在爆发前几天具有相似的自由能和螺度集聚行为, 主要差别是活动区磁螺度的时间变化, 在耀斑前 4 小时, 11158 活动区磁螺度显著减少, 而 12192 活动区则没有。通过分析磁螺度注入率, X2.2 爆发耀斑前磁螺度的巨大减少不是由通过光球层的相反磁螺度注入, 而是由日冕磁场中与 CME 相关的变化引起。另一个重要差别是, 11158 比 12192 活动区具有较大的衰变指数和弱场。

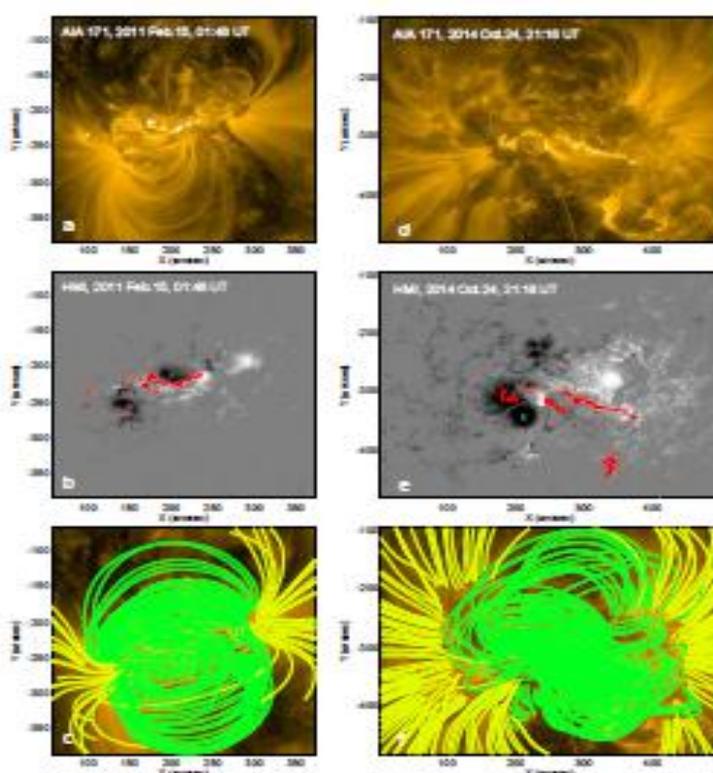


Fig. 1 The X2.2 flare and its hosting AR 11158 (left column) and the X3.1 flare and its hosting AR 12192 (right column). (a)–(b): An AIA 171 Å image and an HMI line-of-sight magnetogram taken in the early phase of the X2.2 flare. The red contours indicate the locations of the flare ribbons as seen in the AIA 171 Å image. (c): Sample NLFF field lines overlaid on the AIA 171 Å image. The closed field lines are colored green, and those field lines reaching the lateral/top boundaries of the computational domain are colored yellow. (d)–(f): same as (a)–(c), but for the X3.1 flare of AR 12192.

图 8.33: NOAA11158 活动区 X2.2 耀斑 (左) 与 12192 活动区 X3.1 耀斑 (右) 比较, 上、中、下表示 AIA、HMI 及非线性无力场外推图

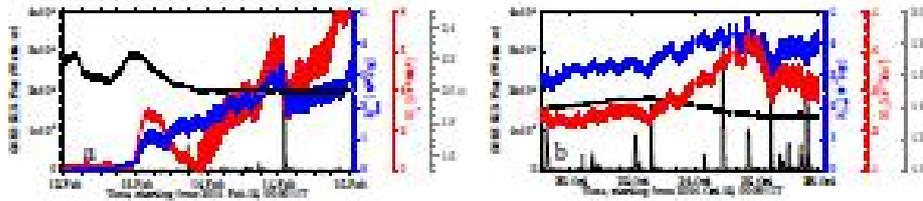


Fig. 4 Temporal variation of helicity H , (red), free magnetic energy E_{free} (blue), decay index n (grey), and GOES soft X-ray (1–8 Å) flux (black) of AR 11158 (a) and AR 12192 (b).

图 8. 34: NOAA 11158 活动 (左) 与 12192 活动区 (右) 的螺度变化 (红)、自由磁能 (蓝) 和衰变指数 (绿) 比较

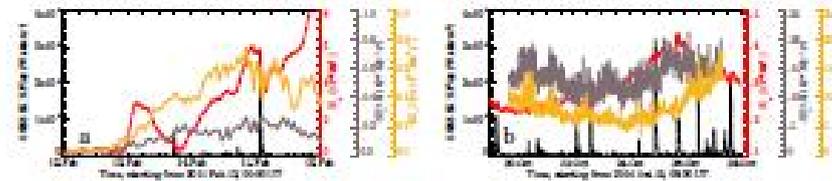


Fig. 5 Temporal variation of helicity H , (red), GOES soft X-ray (1–8 Å) flux (black), negative helicity flux $\frac{dH_-}{dt}$ (grey) and positive helicity flux $\frac{dH_+}{dt}$ (yellow) through the photosphere of AR 11158 (a) and AR 12192 (b).

图 8. 35: NOAA 11158 活动 (左) 与 12192 活动区 (右) 的螺度变化 (红)、GOES 流量 (黑)、负螺度 (灰)、正螺度 (黄) 比较

8.2.12. 2014 年 9 到 10 月 Vernov 观测的太阳 X 射线辐射

Myagkova 等 (2016, Solar Phys, 291, 3439 – 3450) 分析了俄罗斯 Vernov 卫星 RELEC (Detector of the Roentgen and Gamma-ray Emissions) 仪器观测的太阳硬 X 射线及伽马射线辐射, 2014 年 9 到 10 月期间 RELEC 观测到了 18 个耀斑 (>30 keV), 这些耀斑与前一自转周编号 12172 及后一周编号 12192 的同一活动区相连。这些测量与 RHESSI、Konus-Wind、Fermi 观测站、太阳射电望远镜网 (RSTN) 及 Nobeyama 射电日像仪 (NoRH) 数据进行了比较, RELEC 观测的耀斑中约有三分之一发现有 7 ± 2 s 的准周期。

表 8. 6: RELEC 观测到的伽马射线耀斑

Table 1 Solar γ -ray flares detected by RHEC (Wen) from September to October, 2014.

Days/month of 2014	Time, start-end in SXR, human (OOO)	SXR class/opt data	Time, start-end in SXR, human (OOO-RELEC)	QEP period (s)	Other experiments	Notes
1	24/09	17:48-17:50-17:52	C7.0/IN	8.2 ± 2.3	R, K	
2	16/10	12:58-13:02-13:05	M4.3	8.2 ± 1.7	R	
3	17/10	03:10-03:20-03:23	C3.9	No	K	two peaks
4	17/10	04:51-05:00-05:05	C3.6	No	R, J	two peaks
5	18/10	18:59-19:16-19:23	C3.8	5.1 ± 1.4 6.3 ± 0.6	K	
6	19/10	04:17-05:03-05:48	X1.1	No	F	
7	20/10	18:55-19:02-19:04	M1.4	8.1 ± 1.6 9.0 ± 2.9	R, K, J	two peaks
8	25/10	12:13-12:20-12:25	C3.2	No	R, J	
9	26/10	05:43-05:50-05:55	C4.0/SP	No	R, J	
10	27/10	09:06-09:34-09:44	M7.1/IB	No	R	
11	27/10	09:14 (time of radio burst #)	-	No	R	only radio burst
12	27/10	09:01-09:54-09:51	C3.4	No	R	
13	27/10	14:12-14:47-15:09	X2.0/IB	No	R, J	
14	28/10	05:10-05:14-05:17	C3.3	No	F	
15	28/10	01:29-01:58-04:19	C8.1/IF	No	F	
16	29/10	21:13-21:22-21:25	M2.1	7.0 ± 1.2	R, J	in the declining phase
17	29/10	23:00-23:03-23:06	C2.7	No	R, J	
18	30/10	00:04-00:07-00:40	M0.3	6.1 ± 1.5	R, J	

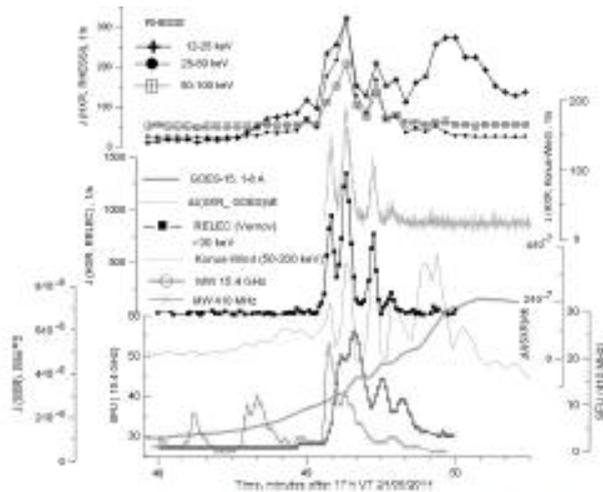


Figure 3 Time profile of the HXR emission measured during a C7.0 solar flare at about 17:49 UT on September 24, 2014 by RHEC (Wen), Konus-Wind and RHESSI experiments, and the SXR emission by GOES, the MW emission (RSTN).

图 8. 36: 2014 年 9 月 24 日 17:49 UT RELEC、Konus-Wind 和 RHESSI 观测的 HXR 辐射时间轮廓及 GOES 和 MW/RSTN 观测的 SXR 辐射

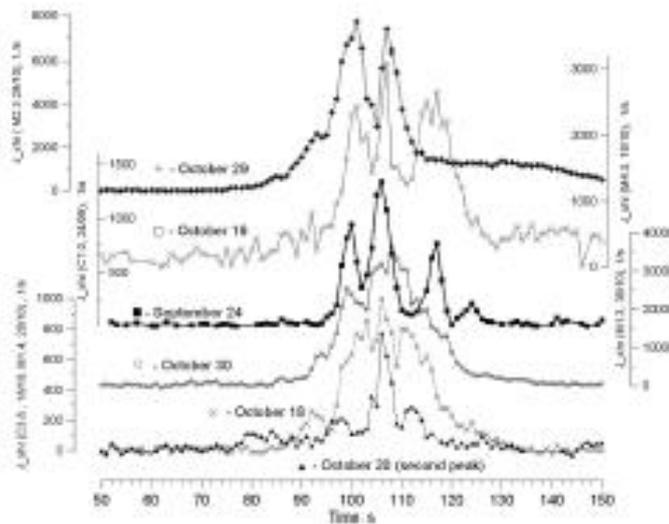


Figure 7 The time profiles of HXR emission with QPP measured by RELEC during six solar flares in 2014: September 24 (C7.0), October 16 (M4.3), October 18 (C3.8), October 20 (M1.4), October 29 (M2.3), and October 30 (M1.3).

图 8.37: RELEC 观测到的六个耀斑的 HXR 辐射轮廓

8.3. 主要科学贡献

12192 是一个很特殊的活动区，面积积极大，磁场位型极其复杂的活动区，耀斑产率很高，但是却几乎没有伴随相应的 CME 现象，对该活动区的研究也主要围绕这种特殊性。一般来说 tether-cutting 重联模型的耀斑应该为 eruptive，常伴随 halo CME。但是这个活动区发生的几个 X 级耀斑均为 tether-cutting 磁重联机制导致，却并没有明显 CME 发生。其原因是由于非势性较低，而且爆发位置较低，在其上有一个很强的束缚的背景场，限制了其爆发性。

● 多波段综合成像研究

➤ 由非热电子直接产生的白光耀斑的 IRIS, Hinode, SDO, 和 RHESSI 观测

用 IRIS, Hinode, SDO 和 RHESSI 等数据综合分析了 2014 年 10 月 22 日 14:02 UT 发生在 NOAA12192 活动区的 X1.6 耀斑，亮核产生了白光 (WL) 耀斑，测量了色球及日冕亮核中等离子特性的时间变化，当发生辐射时，即使在更热的谱线强度增强相当弱，还是能观测到爆发蒸发，时间相关性显示白光辐射是由加速的电子产生，比较估计的能量，连续谱增强是由非热电子直接产生。

➤ 2014 年 9 到 10 月 Vernov 观测的太阳 X 射线辐射

分析了俄罗斯 Vernov 卫星 RELEC 仪器观测的太阳硬 X 射线及伽马射线辐射，2014 年 9 到 10 月期间 RELEC 观测到了 18 个耀斑 (>30 keV)，这些耀斑与前一自转周编号 12172 及后一周编号 12192 的同一活动区相连。这些测量与 RHESSI、Konus-Wind、Fermi 观测站、太阳射电望远镜网(RSTN)及 Nobeyama 射电日像仪(NoRH)数据进行了比较，RELEC 观测的耀斑中约有三分之一发现有 7 ± 2 s 的准周期。

● 物理现象及参量研究

➤ 活动区的限制耀斑

分析了 2014 年 10 月 18 到 29 日 NOAA 12192 活动区的 6 个 X 级和 29 个 M 级耀斑，其中 30 个（包括 6 个 X 级）起源于活动区核，其它 5 个出现在活动区周边。4 个 X 耀斑显示相似的耀斑结构，说明它们是具有相似触发机制的同源耀斑，可能的场面是浮现磁通的光球运动导致相关日冕磁场的剪切，从而产生有利于 tether-cutting 构型。在 5 个周边的 M 级耀斑中个个与喷流 (jet) 活动有关，HMI 垂直磁场显示，耀斑出现之前相关极性的光球磁场在 jet 的足点浮现、汇聚与对消。活动区周边只有一个 M 级耀斑之后跟随 CME。在 20 至 26 日期间，在 40 - 105 Mm 高度之间水平背景磁场的平均衰减指数小于 torus 不稳定性触发的典型阈值，对磁场的强限制可能是 12192 活动区贫 CME 产生的原因。

➤ 限制耀斑与爆发耀斑的比较

从自由能、相对磁螺度和衰变指数角度比较了发生 NOAA 11158 活动区伴随全晕 CME 的 X2.2 爆发耀斑与 12192 活动区没有 CME 的限制耀斑，两个耀斑在爆发前几天具有相似的自由能和螺度集聚行为，主要差别是活动区磁螺度的时间变化，在耀斑前 4 小时，11158 活动区磁螺度显著减少，而 12192 活动区则没有。通过分析磁螺度注入率，X2.2 爆发耀斑前磁螺度的巨大减少不是由通过光球层的相反磁螺度注入，而是由日冕磁场中与 CME 相关的变化引起。另一个重要差别是，11158 比 12192 活动区具有较大的衰变指数和弱场。

➤ 为什么是富耀斑活动区的贫 CME?

比较了这个和其它 4 个活动区：两个富产，两个惰性。SDO/HMI 矢量磁场

图分析显示，富耀斑的 AR 12192 与另外两个富产活动区相似比两个惰性 AR 具有较大的磁通量、电流、自由磁能；与两个富产 AR 相反，它没有沿中性线的强、集中电流螺度，说明缺少由高剪切或缠绕的成熟磁场结构。此外，AR 12192 上方的衰变指数相当低。这些结果说明，富产 AR 总是非常大、具有足够的电流和自由能驱动耀斑，但耀斑是否伴随 CME 似乎与（1）存在成熟的剪切或扭曲核场用作 CME 的种子和（2）对磁拱足够弱的限制密切相关。

➤ 为什么 12192 大活动区是富耀斑而贫 CME？

分析了富耀斑而贫 CME 的 NOAA12192 活动区阻止爆发的磁场条件及相关后果，发现与其他两个产生大耀斑/CME 的活动区 (11429 和 11158)相比，12192 是“大而温和”的活动区，其核区显示较弱非势性、较强的背景场、与耀斑相关的较小的场变化，这些差异存在于密集型指数（例如平均）中，但通常不是在宽泛指数（例如总数）中。12192 活动区大量自由磁能没有转变为产生 CME。这些意外行为显示活动区爆发被一些磁非势相对量限制，被限制的耀斑可能离开较弱的光球和日冕特征。

➤ 在太阳黑子亮桥上方摆动的光墙

辨别出在亮桥(Light Bridge)上面存在着很多亮墙结构(Light Wall)，在 1330, 171 及 131 Å 谱线,墙顶点较亮，而在 H α 谱线，墙顶辐射较低。墙顶上下运动形成震动，震荡的平均高度、振幅、速度及周期分别为 3.6 Mm、0.9Mm、15.4 km/s 和 3.9 分钟，暗示其可能来自于光球下 P 模的泄露。

● 运动与机制研究

➤ MHD 数值驱动

用 MHD 数值驱动方法分析了 NOAA12192 活动区大 X 耀斑的物理机制，在两天时间内，日冕场被光球场慢慢拉紧，逐渐产生一大规模日冕电流片，电流片逐渐上升变薄，在剪切磁场拱之间建立 ether-cutting 重联，导致耀斑。模型成功地再现了耀斑的宏观磁场过程，重联的结果是剪切拱而不是新形成的通量绳，与其它多数 X 耀斑相比，发现该耀斑的磁场爆发效应非常弱。

➤ 一个限制 X 耀斑的磁重联率及能量释放

分析了 2014 年 10 月 22 日 NOAA12192 活动区限制耀斑 X1.6 的能量释放过

程，从三种数据得出的磁重联率与 RHESSI 观测到的硬 X 射线时间轮廓很像，总磁重联通量大概占总无极性通量的 2-4%。在双对数空间，从 27 个爆发事件得出的磁重联通量与 GOES 级别的相关系数为 0.8 左右，限制 X1.6 耀斑很好地落在爆发耀斑的分布上。该事件显示耀斑带存在一个较大的起始分离，但耀斑期间没有运动分离。发现耀斑开始前耀斑带结构存在增强辐射，及连接这些结构的热环。这些观测与通量浮现模型一致，其中新浮现的小通量管与早期存在的大冕环重联。

➤ 三带耀斑的触发过程

通过分析磁场结构的空-时相关性，研究了 NOAA12192 活动区三带耀斑的触发过程，发现正极性的西侧通过侵入负极区成为耀斑触发的地方，这是由于该区剪切场的符号与活动区的大剪切相反，与最近提出的耀斑触发模型一致，该模型提示小的反向剪切 (RS) 磁场扰动可能触发太阳耀斑。还发现 RS 区域偏离 PIL，与理论预测相反。

● CME 特性研究

➤ 与耀斑相随的 CME 中爆炸喷射触发

分析了 NOAA 12192 活动区的唯一一次耀斑(M4.0 级)伴随 CME 事件，暗条的爆发引起了 blow-out 的 jet，从而导致发生 M4.0 耀斑。该耀斑位于活动区的边缘而不是核区，耀斑靠近明显的开放线，在 EUV 以扇形迅速扩张，在耀斑物质与开放线的相互作用下，耀斑变成了爆发耀斑从而导致 CME。在第一个爆发相同的爆发地点，另一个暗条爆发。利用抚仙湖太阳观测站的高空间及时间分辨率 H α 数据和新真空太阳望远镜数据 (NVST)，研究了第二个暗条与附近开放线的相关作用，暗条与开放线的重联构成了一新系统，由于暗条的松解运动，新系统转动，说明 twist 从闭合暗条系统转移到开发系统，此外，twist 似乎从低层传播到高层大气，最终被 CME 带到行星际空间。

➤ NOAA12192 活动区的同源 Jet 驱动的 CME

由搭载在 SDO 及 SOHO 卫星上的仪器观测到的同源日冕 Jet 及其 CME，Jet 起源于 NOAA 12192 大活动区的南边缘处的磁浮现与对消地方，这个活动区在其内部产生了许多非 Jet 大耀斑爆发 (X 及 M 级)，但并无伴随 CME。10 月 20

到 27 日之间，与内部大耀斑爆发相比，来自边缘的六个同源 Jet 形成了 CME。与多数 CME 相比，每个 Jet 驱动的 CME 运动的都比较慢($\sim 200 - 300 \text{ km/s}$)，其角宽度 ($20^\circ - 50^\circ$) 与跨过活动区冕流底相当且需喷流变化，而原先存在的流瞬时膨胀但没被 CME 的通过破坏。在产生 CME 的 Jet 的过渡区等离子体大多数逃离了太阳，而非产生 CME 的 Jet 的过渡区等离子体大多数返回到太阳表面，CME-Jet 比 CME-Jet 往往比较快且持续时间较长。观测显示每个 Jet 和 CME 都是由扭曲场的开放重联导致的，扭曲场从 Jet 底爆发，而爆发场并没有像原先看到的喷流 CME 变成等离子体团，相反，喷流指引的冕流底环被重联环的 twist 吹走。

● 对地效应

该事件既无高能粒子事件也无地磁暴。

8.4. 有关影视资料

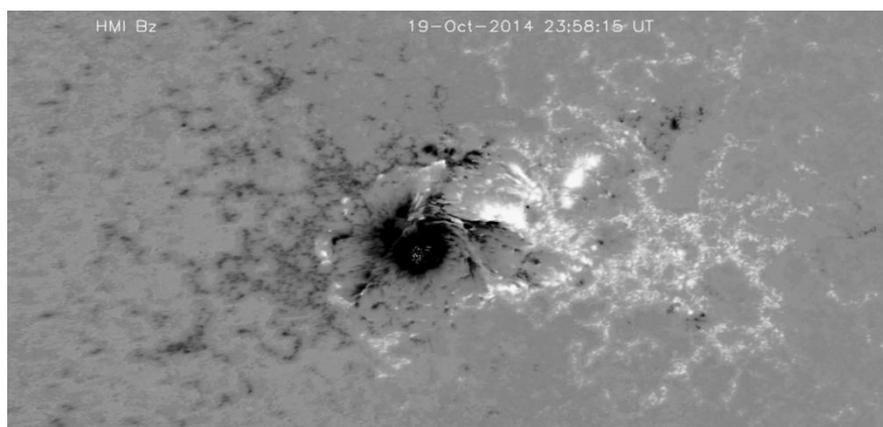


图 8. 38 : 2014 年 10 月 24 日 21UT HMI 观测的 12192 活动区矢量磁图 ([Chen 2015 ApJL 808 L24](#))

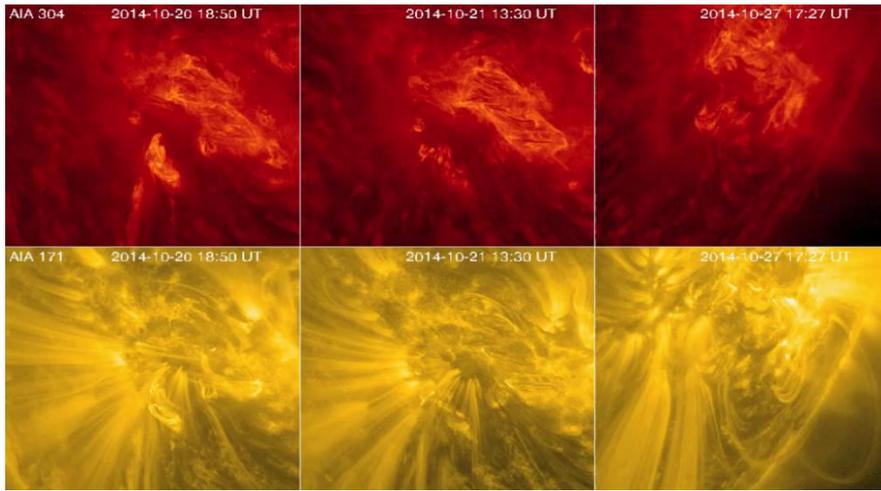


图 8.39: 2014 年 10 月 24 日 AIA304、94A 观测的 12192 ([Chen 2015 ApJL 808 L24](#))

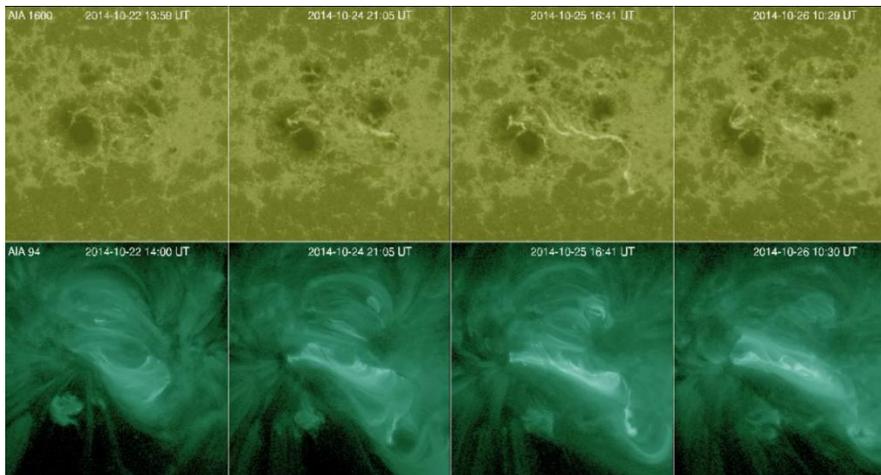


图 8.40: 2014 年 10 月 24 日 AIA304、94A 观测的 12192 ([Chen 2015 ApJL 808 L24](#))

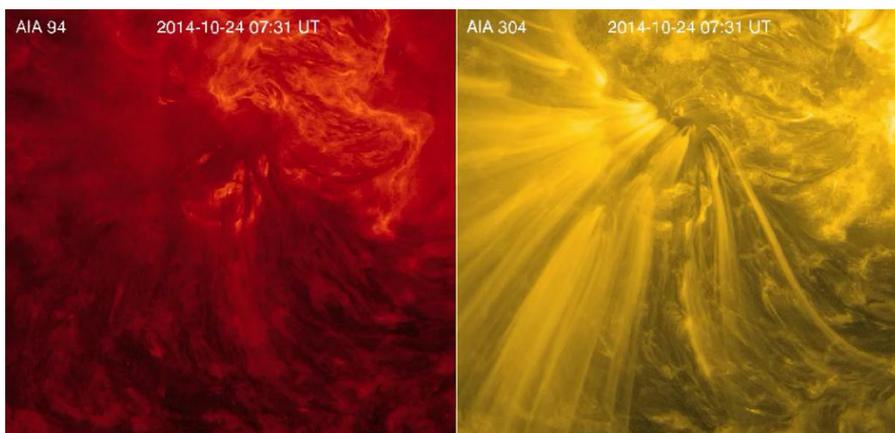


图 8.41: 2014 年 10 月 24 日 AIA304AJet 观测的 12192 ([Chen 2015 ApJL 808 L24](#))

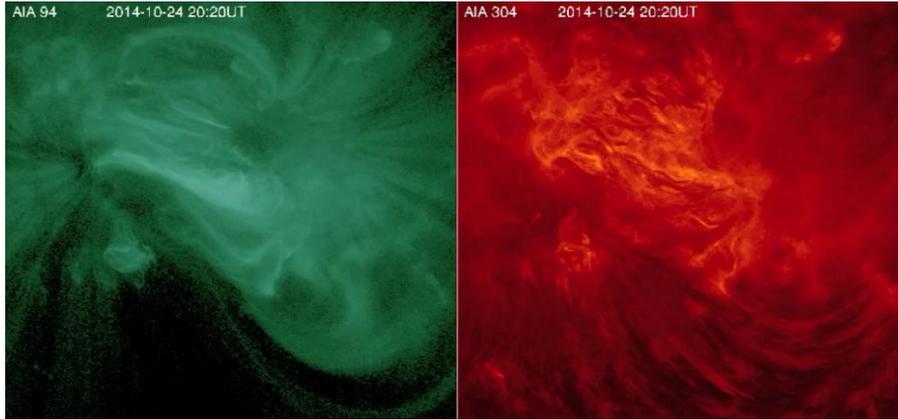


图 8. 42: 2014 年 10 月 24 日 AIA304AJet 观测的 12192 ([Chen 2015 ApJL 808 L24](#))

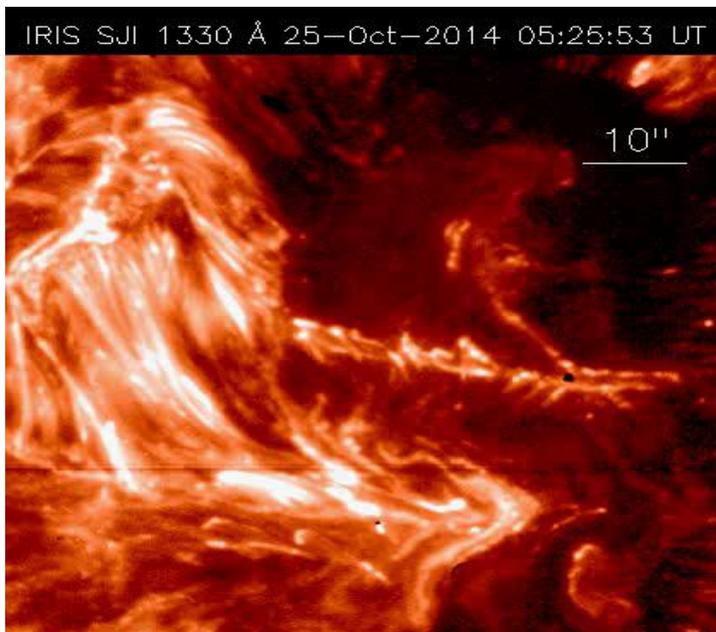


图 8. 43: 2014 年 10 月 25 日 IRIS 1330 Å 观测的 12192 活动区亮墙([Yang, 2015, ApJL, 804, L27](#))

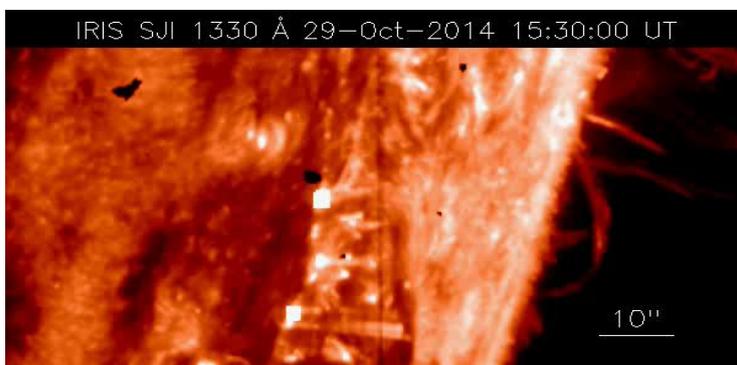


图 8. 44: 2014 年 10 月 29 日 IRIS 1330 Å 观测的 12192 活动区亮墙([Yang, 2015, ApJL, 804, L27](#))

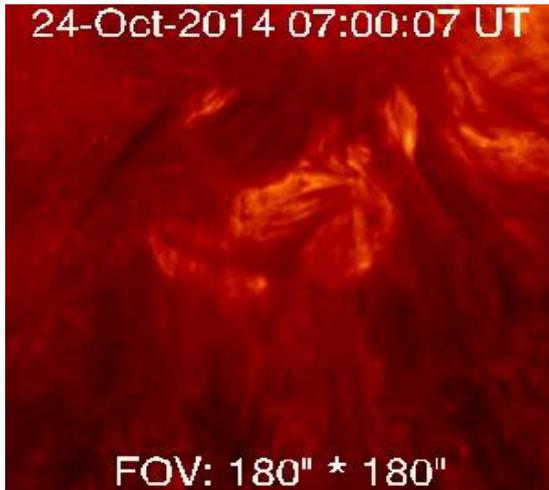


图 8. 45:2014 年 10 月 21 日 AIA304 Å观测的 12192 活动区爆发([Li, 2015, ApJL, 814, L13](#))

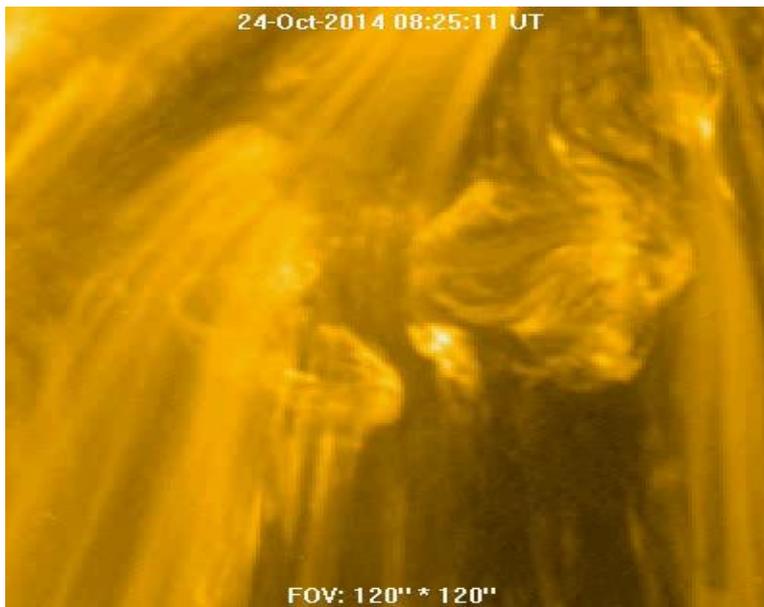


图 8. 46: 2014 年 10 月 24 日 AIA171Å观测的 12192 活动区([Li, 2015, ApJL, 814, L13](#))

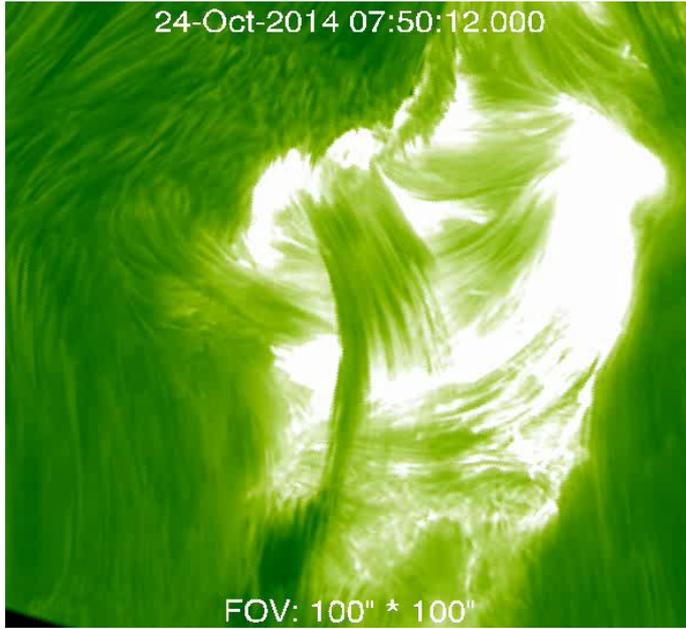


图 8. 47: 2014 年 10 月 24 日 AIA304 Å 观测的 12192 活动区([Li, 2015, ApJL, 814, L13](#))



图 8. 48: 2014 年 10 月 24 日 AIA171 Å 观测的 12192 活动区([Li, 2015, ApJL, 814, L13](#))

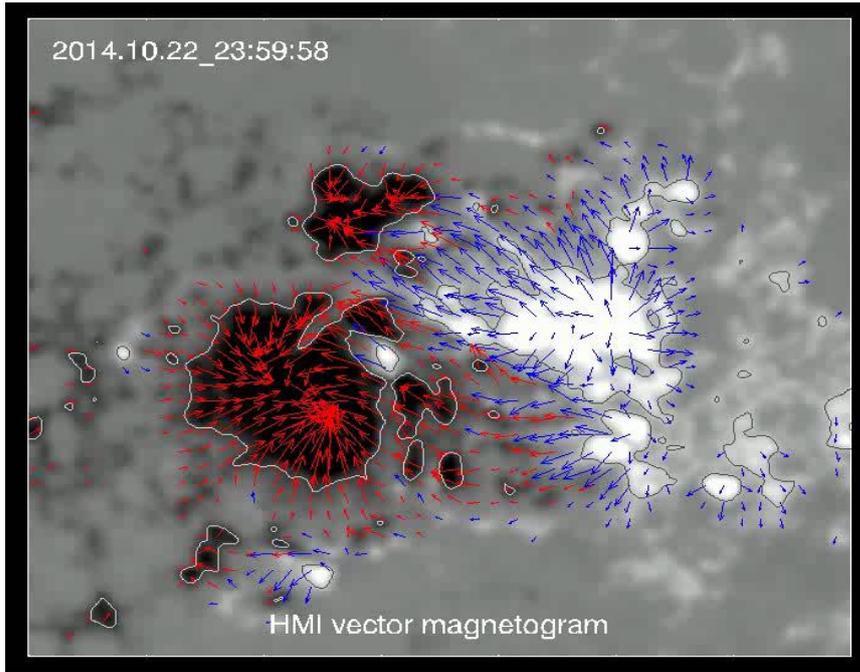


图 8. 49: 2014 年 10 月 24 日 HMI 观测的 NOAA12192 活动区([Jiang, 2016, APJ, 828, 62](#))

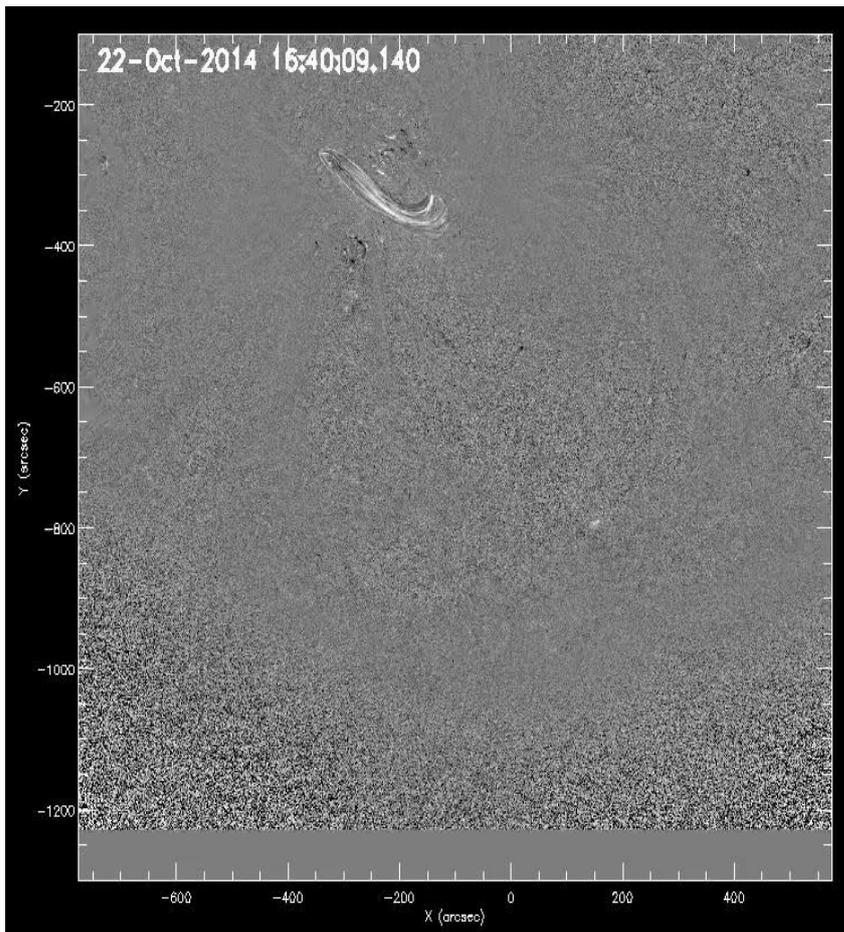


图 8. 50: 2014 年 10 月 22 日 AIA193Å观测的 12192 活动区 Jet([Panesar 2016, APJL, 822, L23](#))

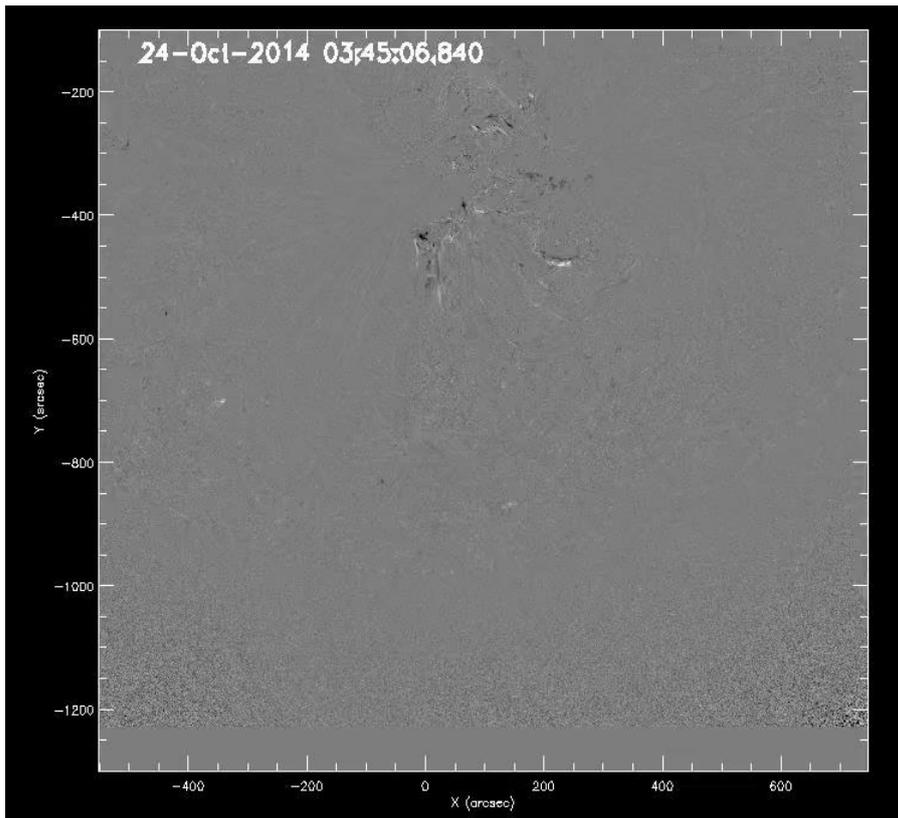


图 8. 51: 2014 年 10 月 24 日 AIA193Å观测的 12192 活动区 Jet([Panesar 2016 , APJL, 822, L23](#))

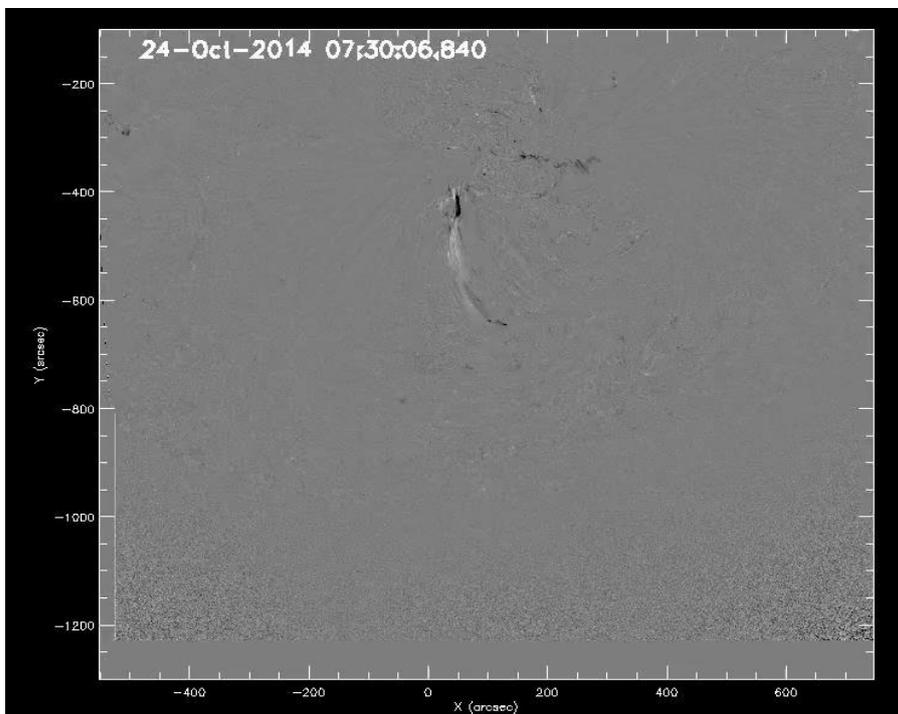


图 8. 52: 2014 年 10 月 24 日 AIA193Å观测的 12192 活动区 Jet([Panesar 2016 , APJL, 822, L23](#))

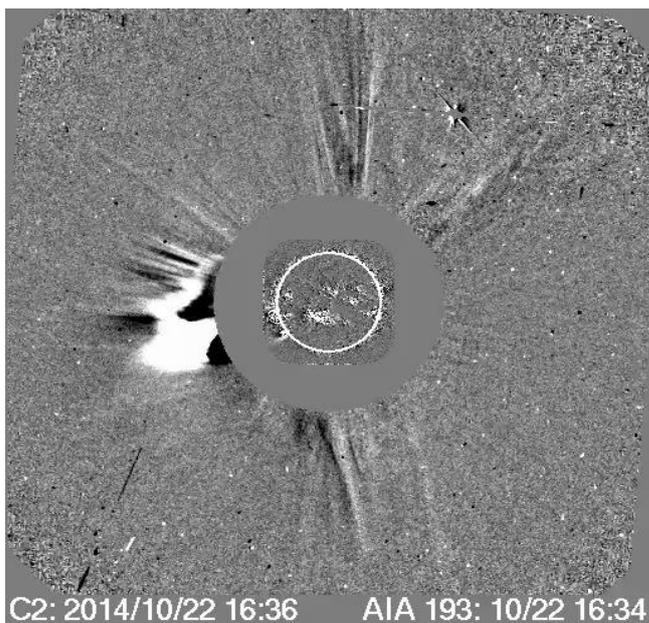


图 8. 53: 2014 年 10 月 24 日 LASCO C2 观测的 CME([Panesar_2016 . APJL. 822. L23](#))

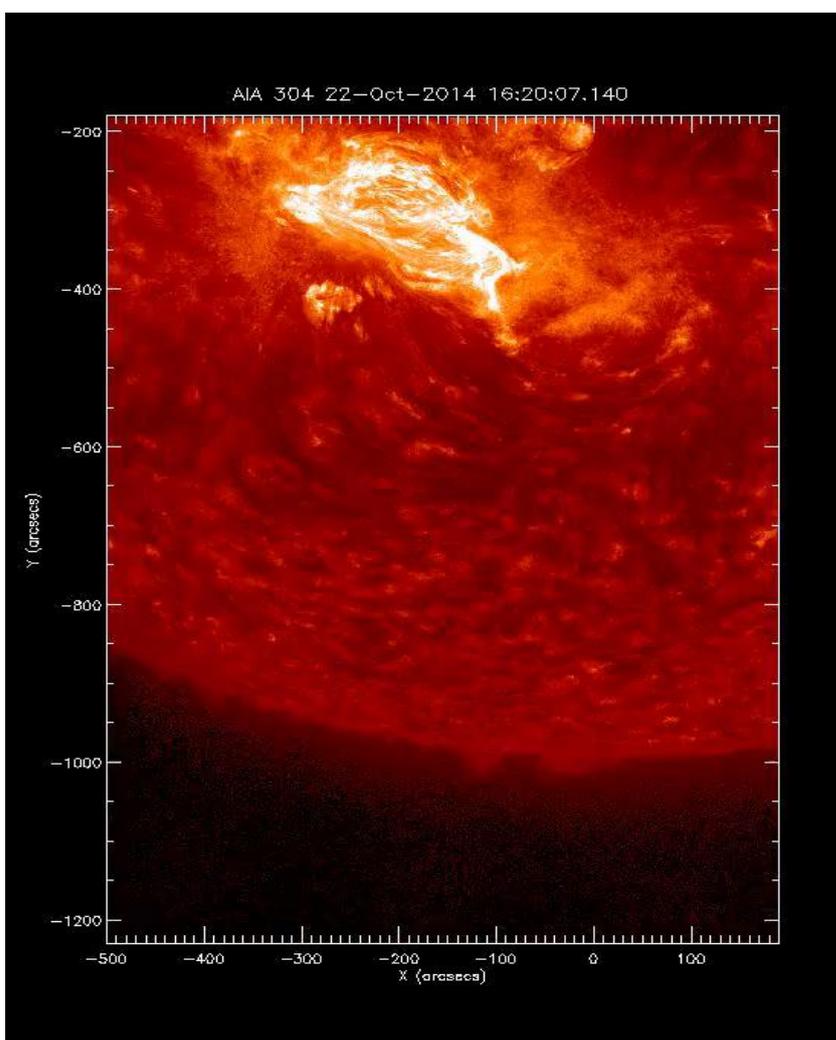


图 8. 54: 2014 年 10 月 24 日 AIA 304 Å 观测的 12192 活动区([Panesar_2016 . APJL. 822. L23](#))

8.5. 主要参考文献

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* 主要空间太阳观测仪器数据

卫星名称	设备名称	数据描述	数据网址
SDO (Solar Dynamics Observatory)	HMI (Helioseismic and Magnetic Imager)	太阳全日面光球矢量磁场数据	http://hmi.stanford.edu/
	AIA (Atmospheric Imaging Assembly)	太阳 EUV / UV 波段成像数据	http://aia.lmsal.com/
	EVE (Extreme Ultraviolet Variability Experiment)	太阳 EUV 波段光谱和流量数据	http://lasp.colorado.edu/home/eve/
IRIS (Interface Region Imaging Spectrograph)	/	太阳 UV 波段光谱成像数据	http://iris.lmsal.com/
Hinode	SOT (Solar Optical Telescope)	太阳光球和色球成像数据； 太阳光球矢量磁场数据	http://darts.isas.jaxa.jp/solar/hinode/
	XRT (X-Ray Telescope)	太阳 X 射线波段成像数据	
	EIS (EUV Imaging Spectrometer)	太阳 EUV 波段光谱成像数据	
SOHO (Solar and Heliospheric Observatory)	MDI (Michelson Doppler Imager)	太阳全日面纵向磁场数据	http://soi.stanford.edu/
	EIT (Extreme-ultraviolet Imaging Telescope)	太阳 EUV 波段成像数据	https://umbra.nascom.nasa.gov/eit/
	LASCO (Large Angle)	太阳白光日冕仪成像数据	https://sohowww.nascom.nasa.gov/

	Spectroscopic Coronagraph)		v/data/
STEREO (Solar Terrestrial Relation Observatory)	EUVI (Extreme Ultraviolet Imager)	太阳 EUV 波段 成像数据	https://stereo-ssc .nascom.nasa.gov
	COR1/COR2 (Coronagraph 1/2)	太阳白光日冕仪 成像数据	v/data.shtml
GOES (Geostationary Operational Environmental Satellite)	XRS (X-Ray Sensor)	太阳软 X 射线流 量数据	https://www.ngdc .noaa.gov/stp/sat
	EPS (Energetic Particle Sensor)	太阳质子流量数 据	ellite/goes/
RHESSI (Reuven Ramaty High-Energy Solar Spectroscopic Imager)	/	太阳硬 X 射线光 谱成像数据	https://hesperia. gsfc.nasa.gov/rh essi3/
PROBA2 (Project for On Board Autonomy 2)	SWAP (Sun Watcher with Active Pixels and Image Processing)	太阳 EUV 波段 成像数据	http://proba2.sid c.be/
	LYRA (Large Yield Radiometer)	太阳 UV-XUV 波 段流量数据	