南京大学120周年校庆
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太阳高温等离子体的探测及其对恒星耀发的启示

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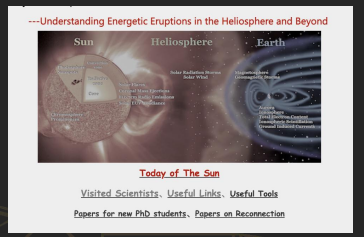
南京大学天文与空间科学学院

主要内容

- 耀斑的多波段观测
- 耀斑热等离子体的动力学过程
- 热磁通量绳的观测发现及其作用
- 耀斑/CME标准模型对理解恒星耀发的启示

Benz 2017, Living Review in Solar Physics
Shibata & Magara 2011, Living Review in Solar Physics
Priest & Forbes 2002, The Astronomy and Astrophysics Review



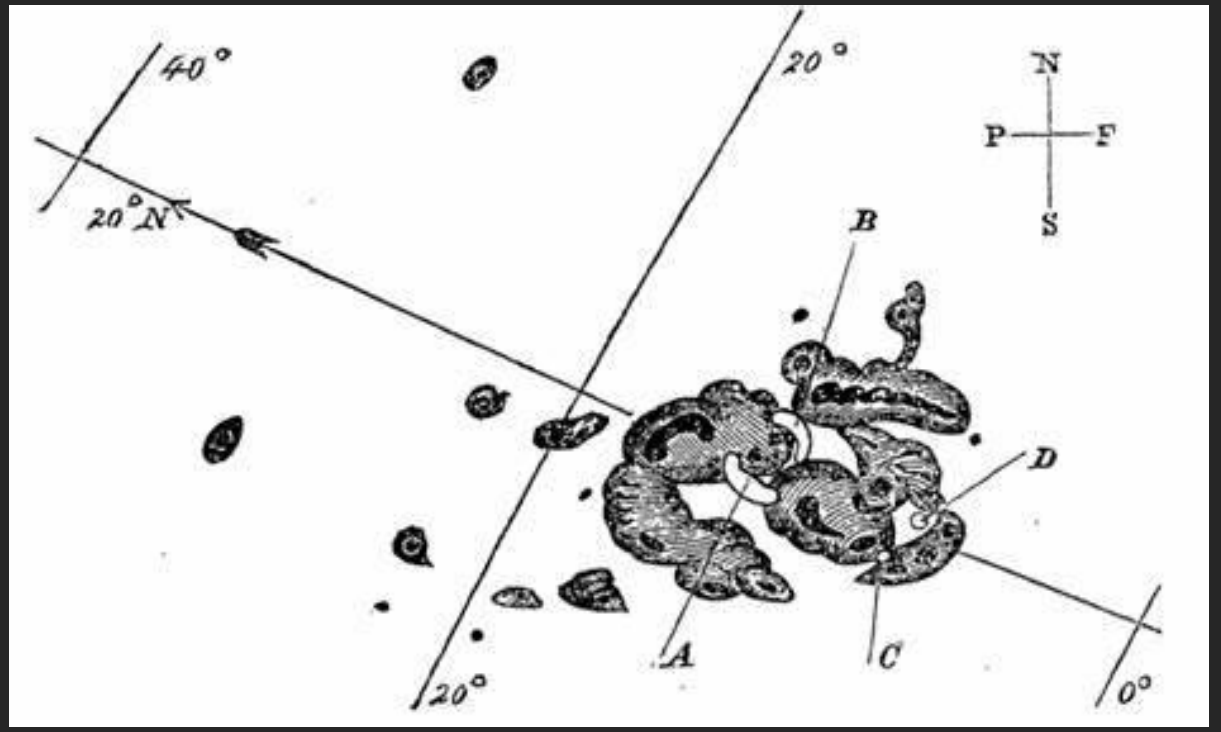
1. 耀斑的多波段观测——第一例白光耀斑观测

Flare definition:

–A flare is defined as a sudden, rapid, and intense variation in brightness. Its radiation is emitted across virtually the **entire electromagnetic spectrum**, from radio waves, through optical emission to x–rays and gamma rays.

–The energy released during a flare is typically on the order of **10^{27} ergs per second**. Large flares can emit **up to 10^{32} ergs of energy**. less than **one–tenth of the total energy ($3.8*10^{33}$)** emitted by the Sun every second.

–The first solar flare recorded in astronomical literature was on September 1, 1859. Two scientists, **Richard C. Carrington and Richard Hodgson**, were independently observing sunspots at the time, when they viewed a large flare in white light.



https://hesperia.gsfc.nasa.gov/sftheory/flare.htm

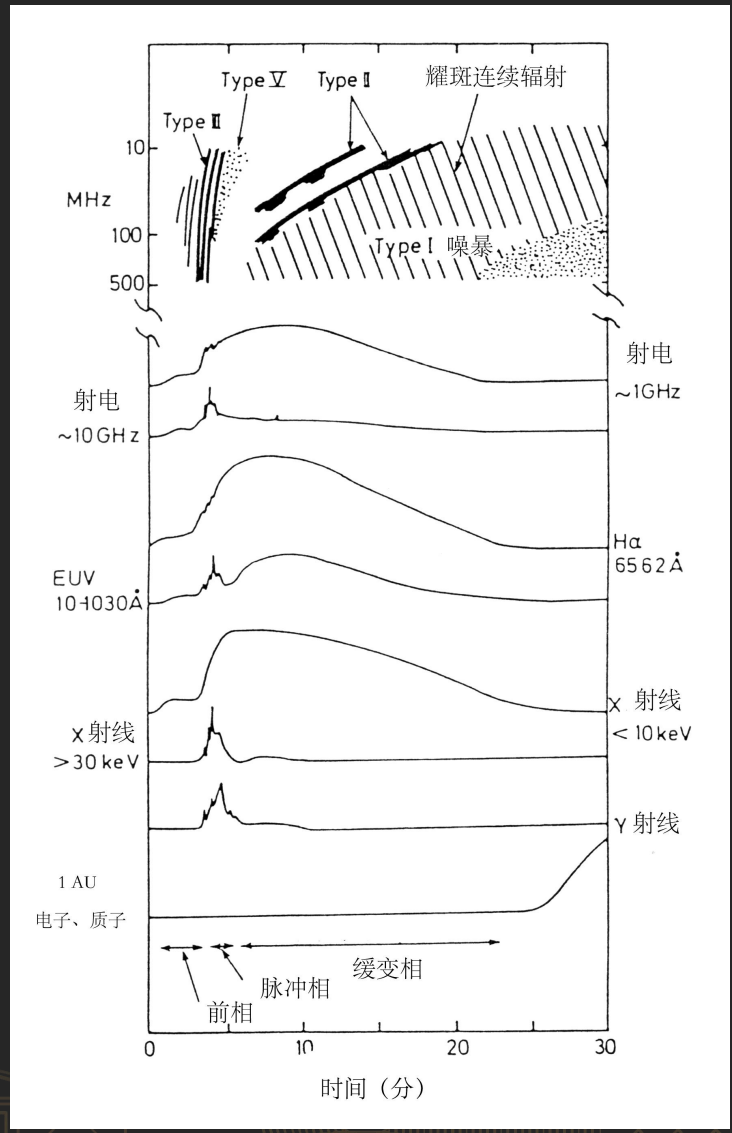
1. 耀斑的多波段观测——光变

前相： 一般时标为几分钟到几十分钟。在此阶段，软X射线、EUV和射电辐射已开始增强，Hα也有所增亮。

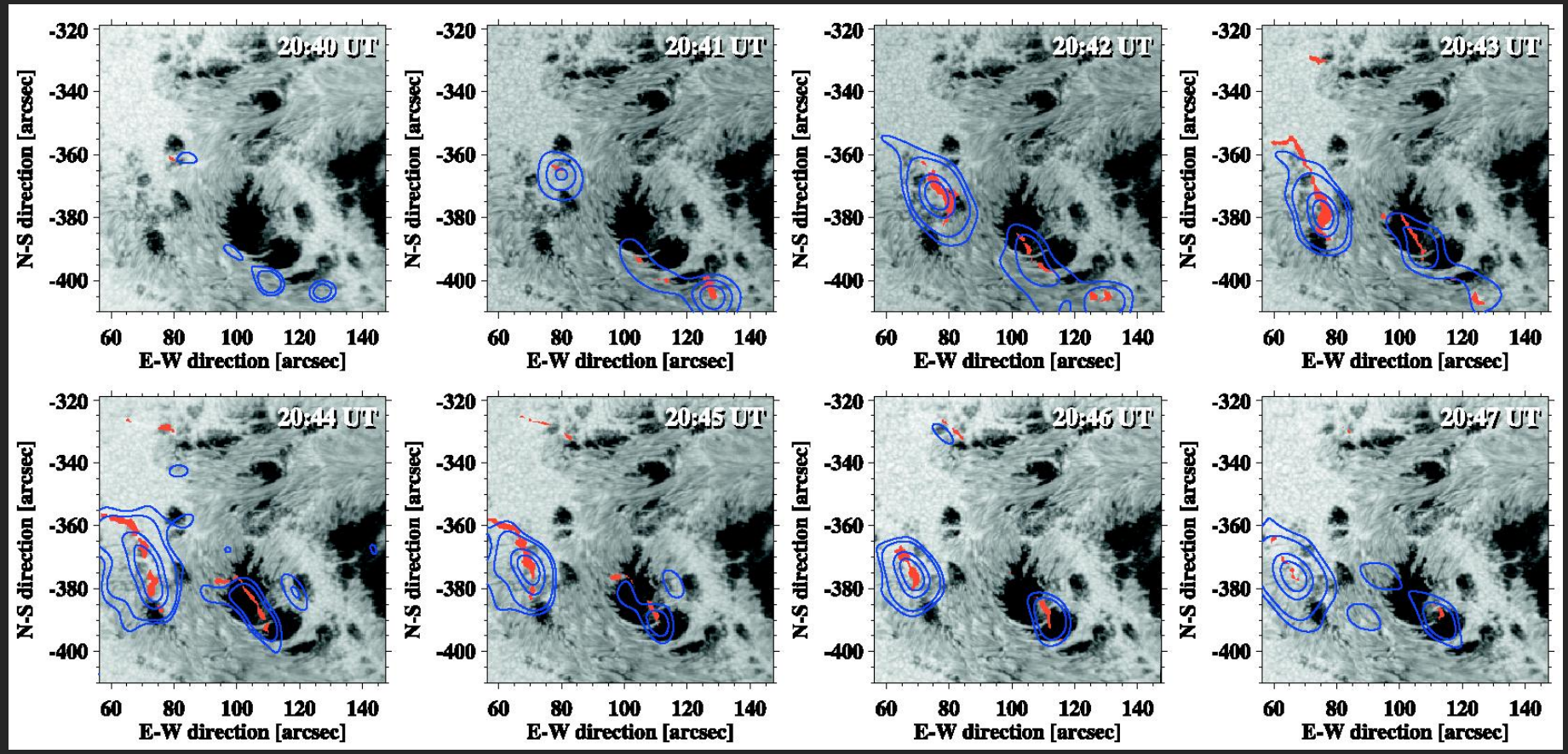
闪相： 一般时标为几分钟到几十分钟。其特征是耀斑Hα谱线的强度和宽度迅速增加，软X射线和EUV辐射也不断增强。在闪相，硬X射线和微波爆发常表观为脉冲型的突然增强，并随后较快地衰减，持续时间仅为几分钟，称为脉冲相。有些耀斑可以不出现脉冲相，其X射线辐射和微波爆发表现为较缓慢的增强，属缓变型。

缓变相： 其特征是Hα和软X射线强度逐渐缓慢减弱，持续时间为几十分钟到1~2小时。

Schematic summary



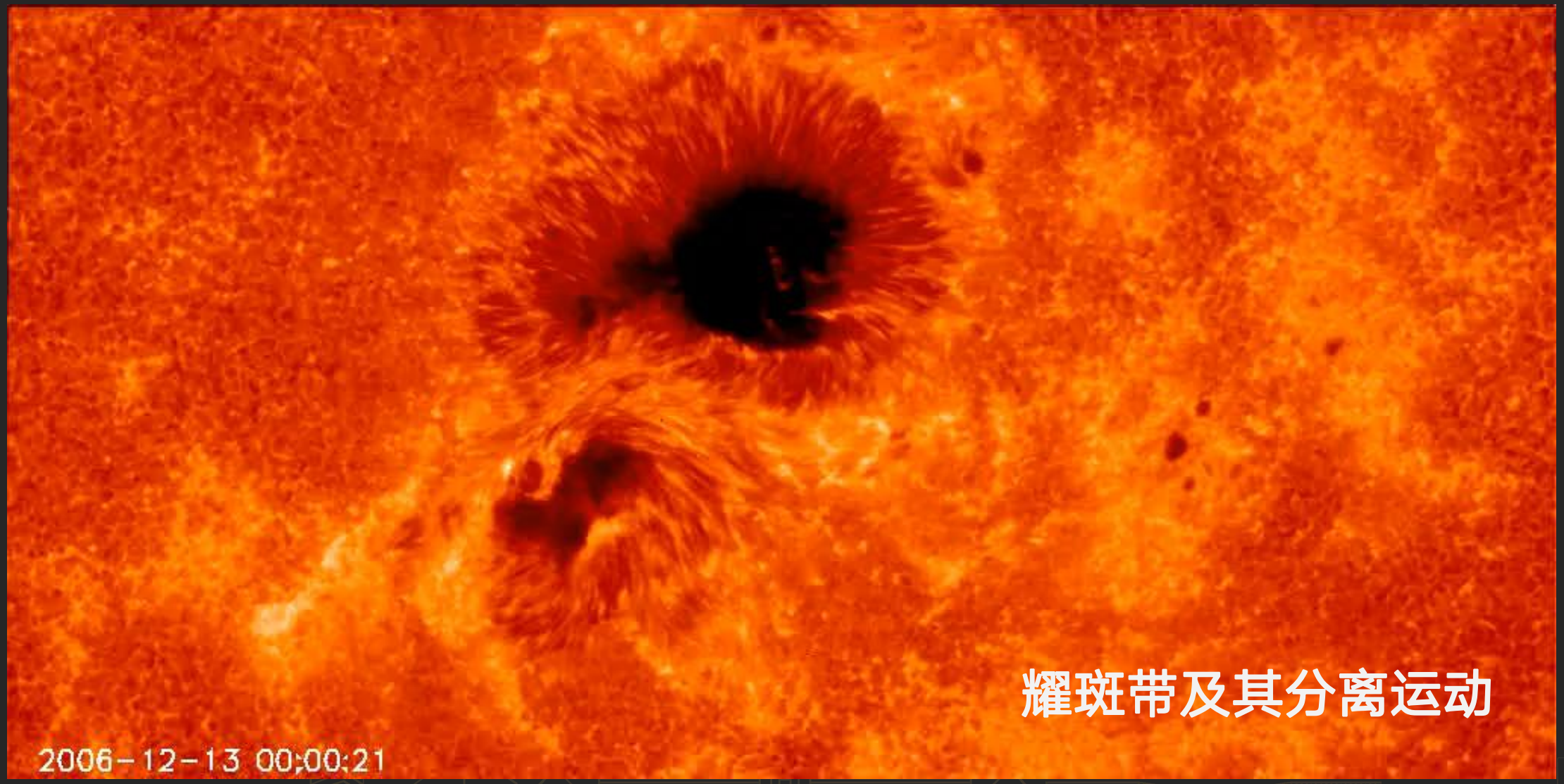
1. 耀斑的多波段观测——光球特征



- The X10 WLF of 2003 October 29 (S15 W02) by BBSO at 1.56 μm
- Blue: RHESSI HXR 50-100 keV Red: NIR continuum

(Xu et al. 2004)

1. 耀斑的多波段观测——色球特征



耀斑带及其分离运动

1. 耀斑的多波段观测——日冕特征

软X射线辐射及其耀斑形态

Yohkoh/XRT新观测

-绝大部分耀斑都有强度不等的软X射线辐射增强。

-它主要由高度电离的离子的线辐射以及由轫致辐射、束缚—自由跃迁和双光子发射所产生的连续辐射组成，具有热的或准热的起源，对应的温度为2×10^6—6×10^7 K。

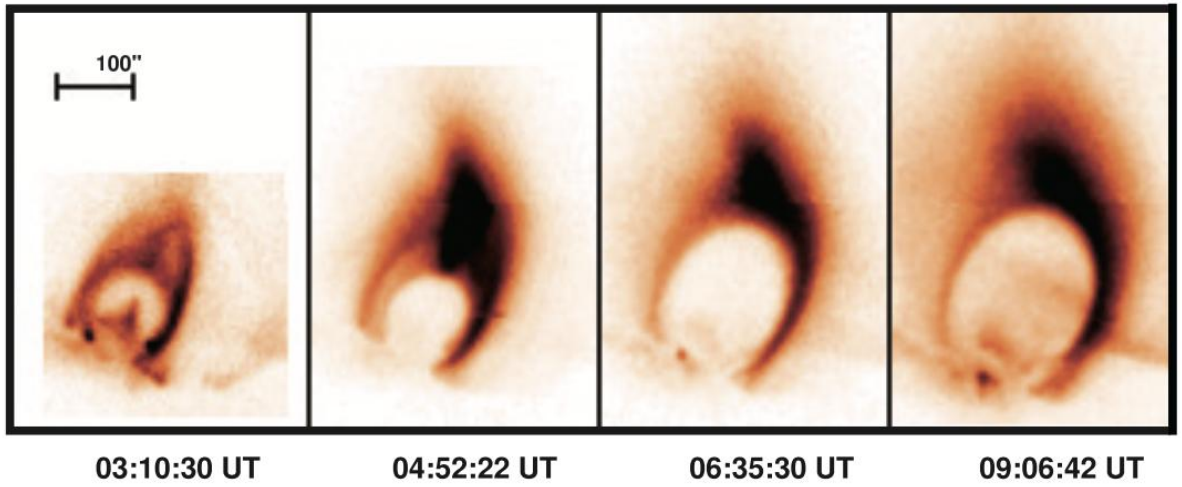


Figure 4: A soft X-ray image of an LDE flare with cusp shaped-loop structure, observed on Feb. 21, 1992 (Tsuneta *et al.*, 1992a; Tsuneta, 1996). Shown in reversed contrast.

1. 耀斑的多波段观测——日冕特征

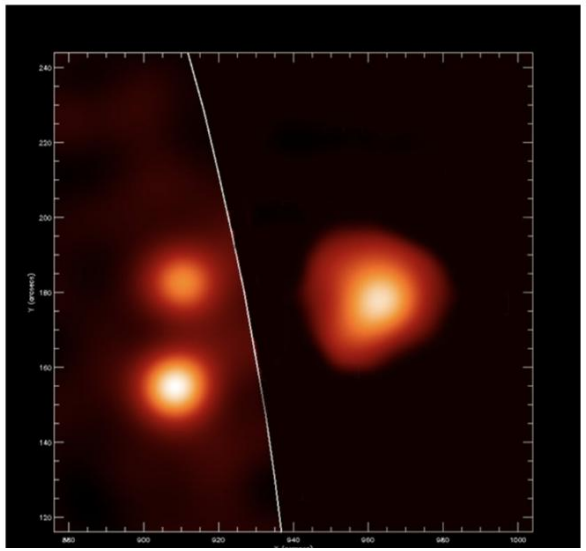


Fig. 10 Reconstructed (CLEAN) image of SOL2006-07-13T14 in hard X-rays observed by the RHESSI satellite. The *curved line* indicates the limb of the photosphere. The displayed energy range 12–50 keV is dominated by the low energies, where the coronal source (*right*) prevails. Two footpoints (*left*) are clearly visible on the disk. Image courtesy of Marina Battaglia, for details see Battaglia and Benz (2008)

RHESSI新发现

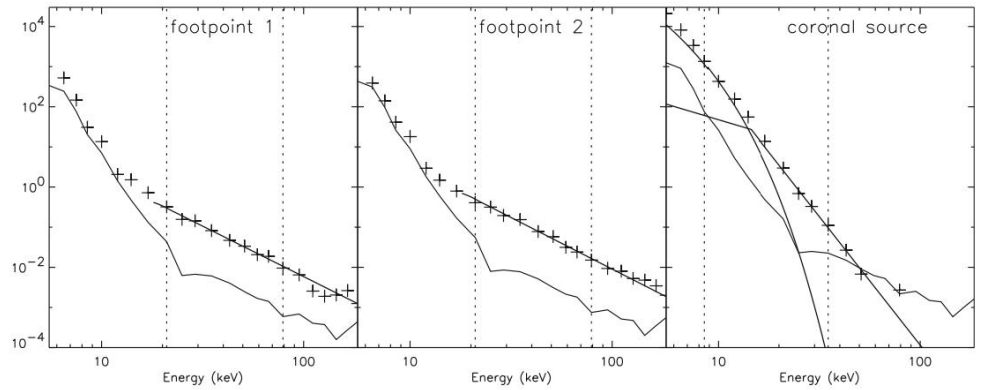


Fig. 11 Spectra of the three sources shown in Fig. 10 as observed by RHESSI at peak time. *Left and middle* spectra of footpoints. A power-law was fitted in energy between the *dotted lines*. *Right* spectrum of the coronal source. A power-law and a thermal population was fit between the *dashed lines*. Image reproduced with permission from Battaglia and Benz (2006), copyright by ESO

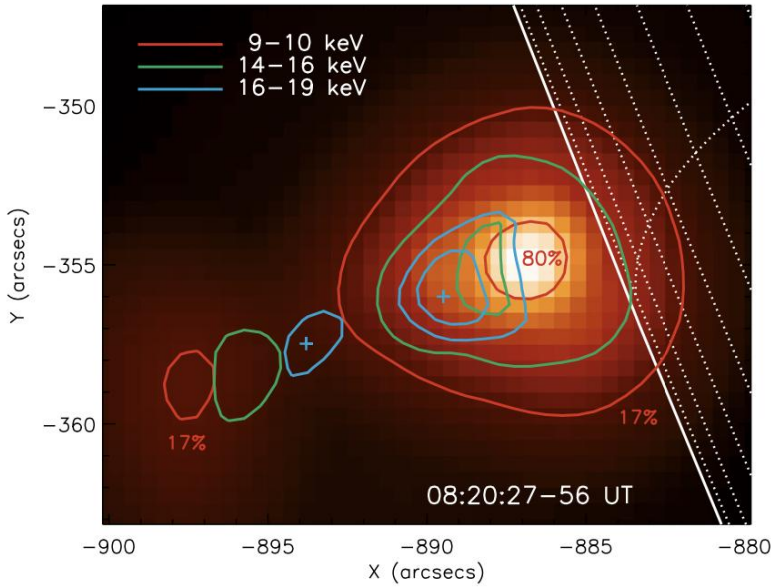


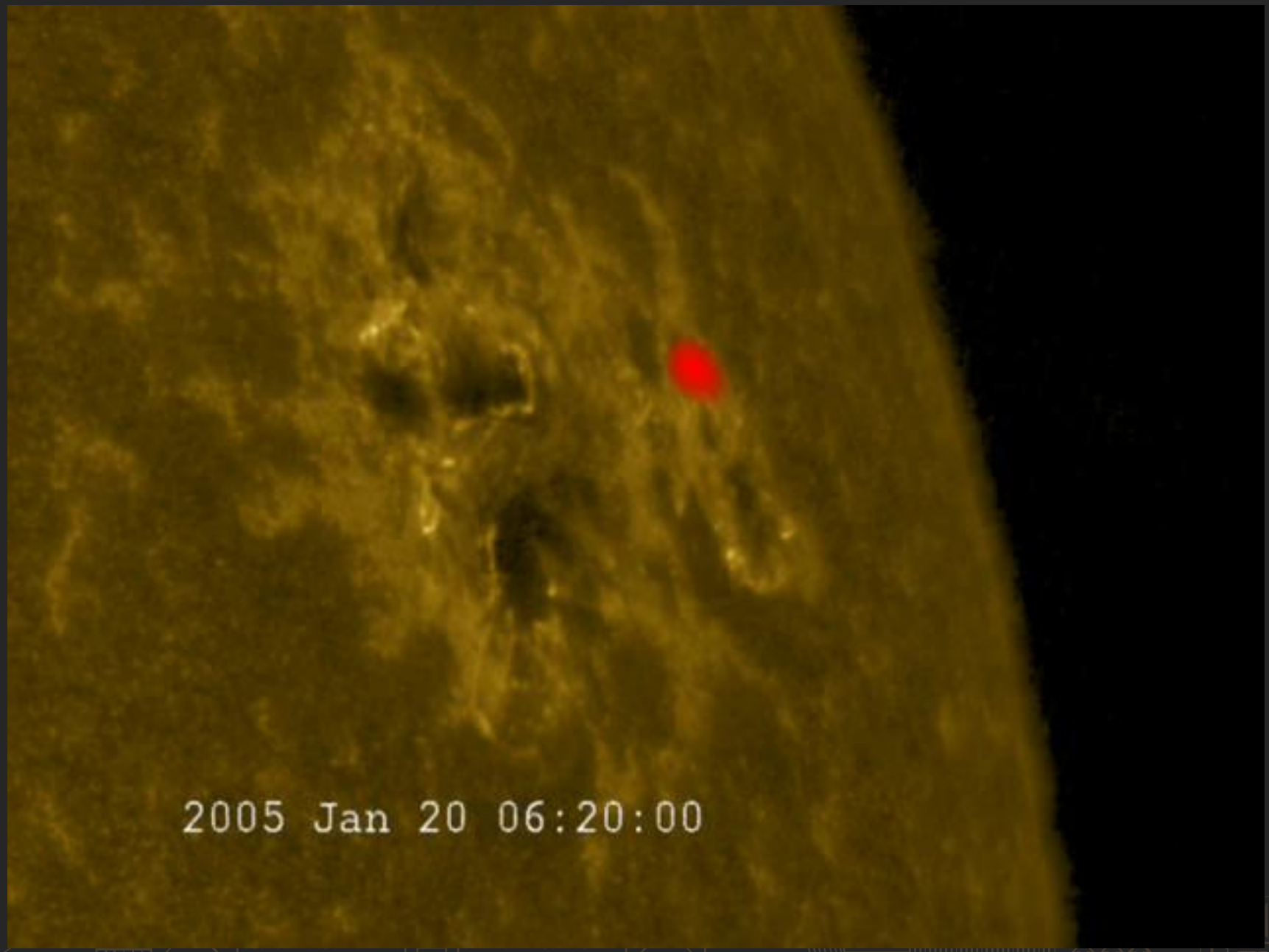
Fig. 17 RHESSI observations of the flare SOL2002-04-30 with soft X-ray emissions that extend beyond the loop top. The footpoints are occulted by the solar limb. In the lowest energy band (9–10 keV, *red*) two contours are shown representing 17 and 80% of the maximum brightness. Image reproduced by permission from Liu et al. (2008), copyright by AAS

硬X射线源和能谱

硬X射线日冕源的结构和分布

重联区被认为在日冕源和环顶源之间

RHESSI flare observations of soft X-rays (*red* 8–12 keV) and hard X-rays (*blue* 20–50 keV) overlaid on a 1700 A background.



2. 耀斑动力学——Flare标准模型:

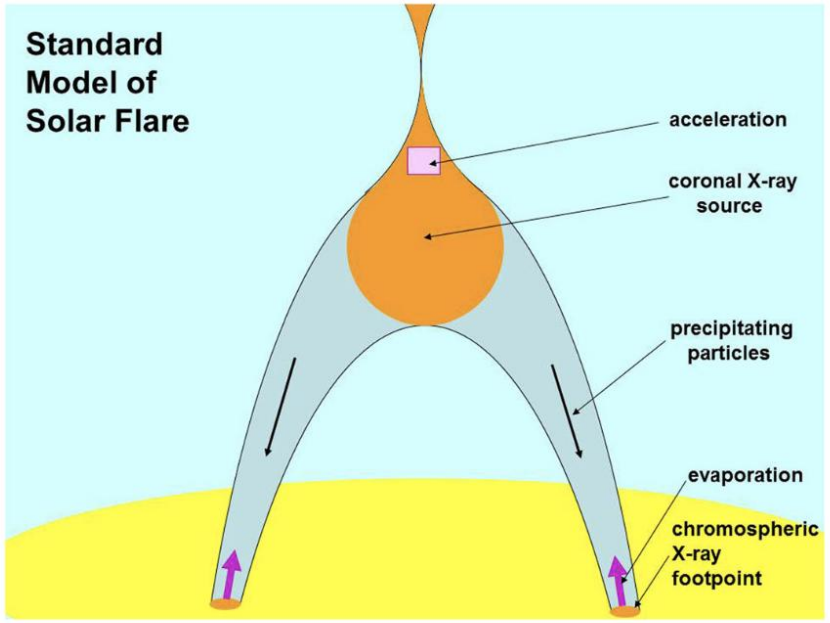


Fig. 13 A schematic drawing of the standard flare scenario assuming energy release at high altitudes

- **It is not a quantitative theory, but an attempt to order some, but not all observations.**
- **The acceleration process is not part of the scenario.**

Based on the following observations:

– Correlation of soft X-ray flux with cumulative hard X-ray flux (Neupert effect)

– Hard X-rays (>25 keV) often originate from sources at the footpoints of the loop emitting soft X-rays.

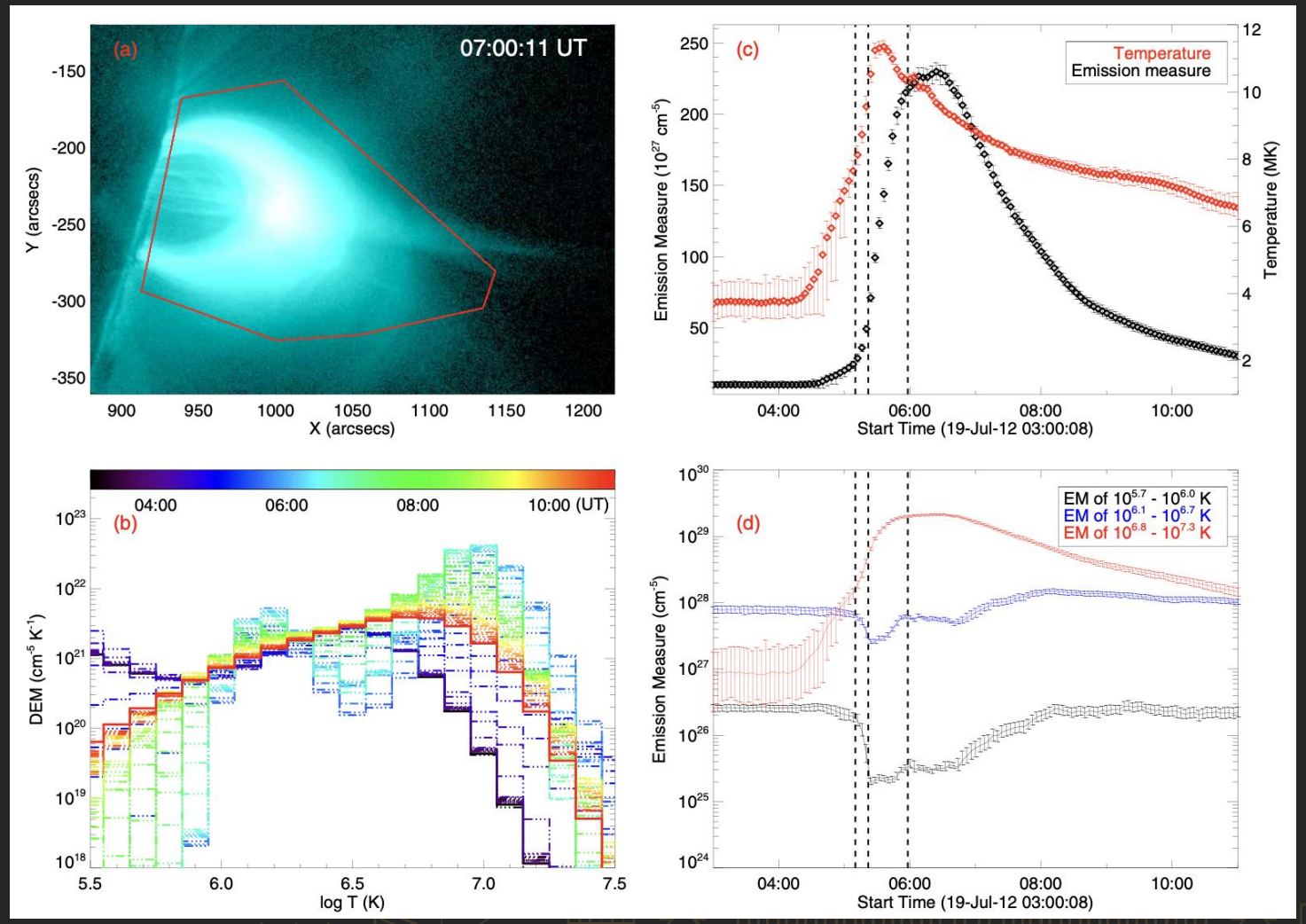
– The coronal hard X-ray source is occasionally observed to be above the soft X-ray loop (Masuda et al. 1994).

– The energy in accelerated electrons tends to be larger than the thermal energy contained in the soft X-ray source.

– The hard X-ray spectrum of non-thermal electrons in the coronal source is considerably softer than in the footpoints, suggesting that the latter is a thick target.

– The emission measure of the soft X-ray source greatly increases during the impulsive phase, indicating that chromospheric material is evaporating during this period.

2. 耀斑动力学——温度和密度变化



- Plasma are heated to 10-20 MK from the evolution of DEM curves
- Temperature peaks before EM
- EM at the temperature of 1-5 MK decreases
- EM above 5MK increases

2. 耀斑动力学——蒸发模型的强有力证据

doi:10.1088/0004-637X/699/2/968

VELOCITY CHARACTERISTICS OF EVAPORATED PLASMA USING *HINODE*/EUV IMAGING SPECTROMETER

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Received 2009 February 12; accepted 2009 April 30; published 2009 June 17

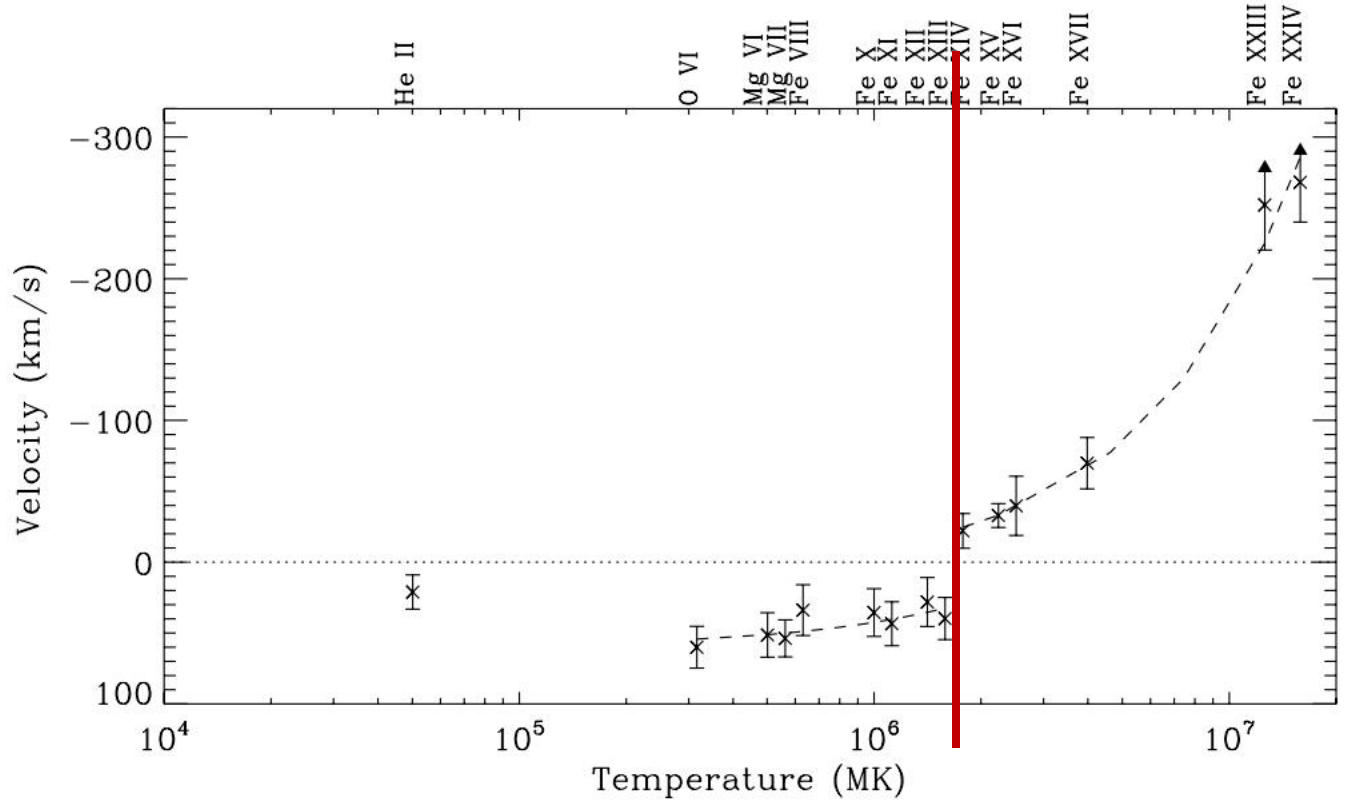
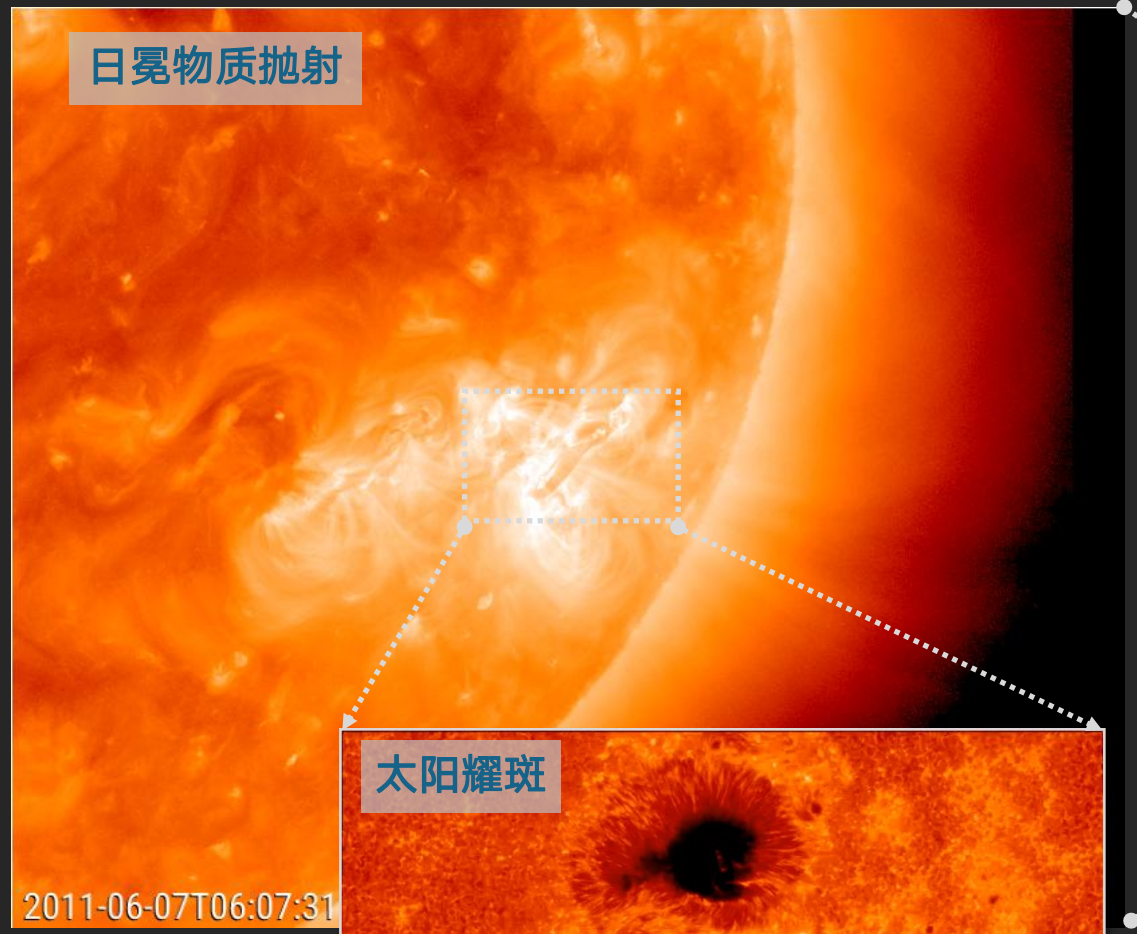
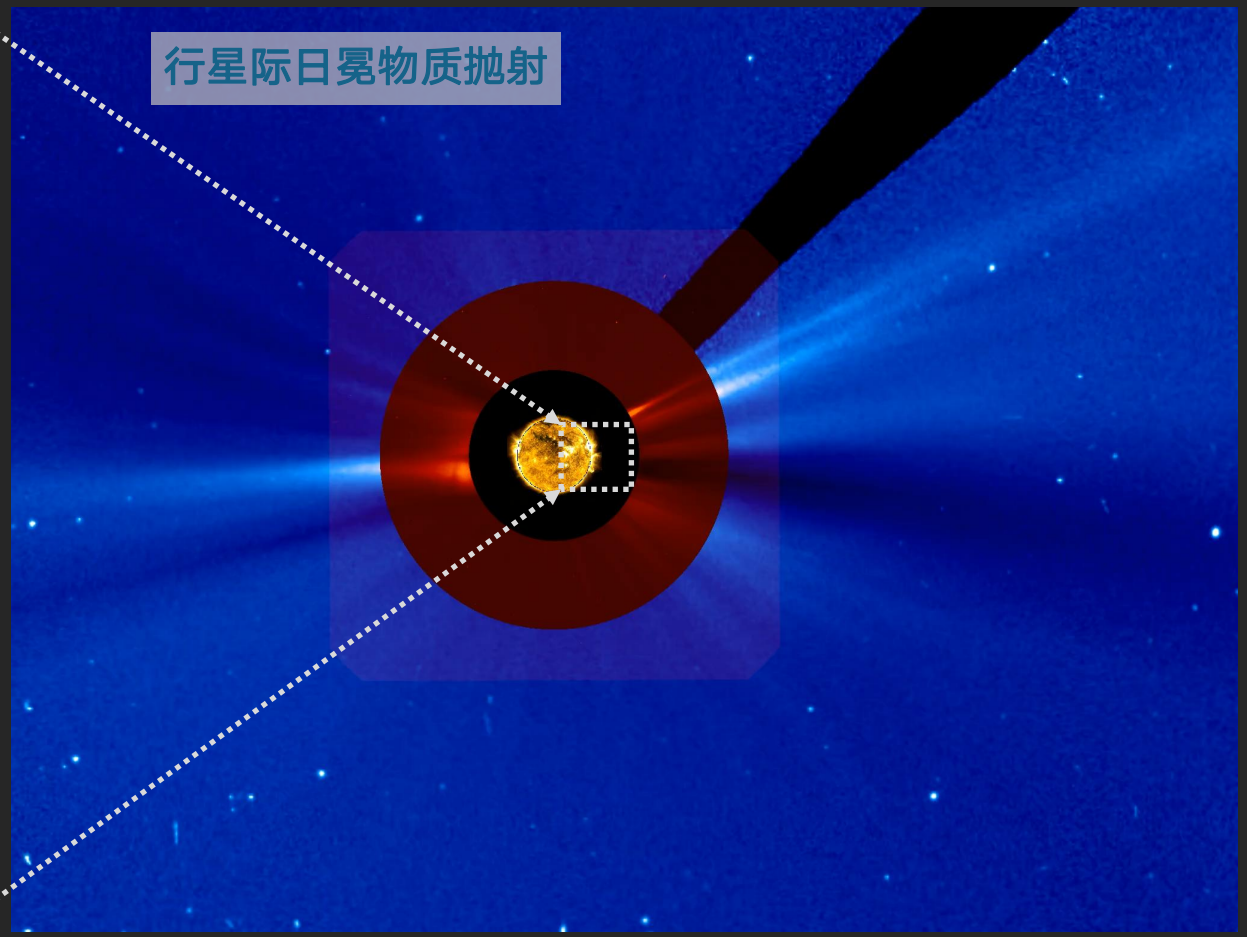


Figure 5. Plasma velocity from a flare footpoint at ~14:14:51 UT as a function of temperature for each of the emission lines used in this study. The dashed lines represent a weighted least-squares fit to the data points from 0.5 to 1.5 MK and 2.0 to 16 MK.

为什么会有耀斑？

3. 磁通量绳的观测发现——日冕物质抛射





3. 磁通量绳的观测发现——CME和耀斑的因果之争

Solar flares and magneti

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Newton, H. W.

No abstract

Publication: Monthly No

Pub Date: 1943

DOI: 10.1093/mn

Bibcode: 1943MNRA

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FEEDBACK

The solar flare myth

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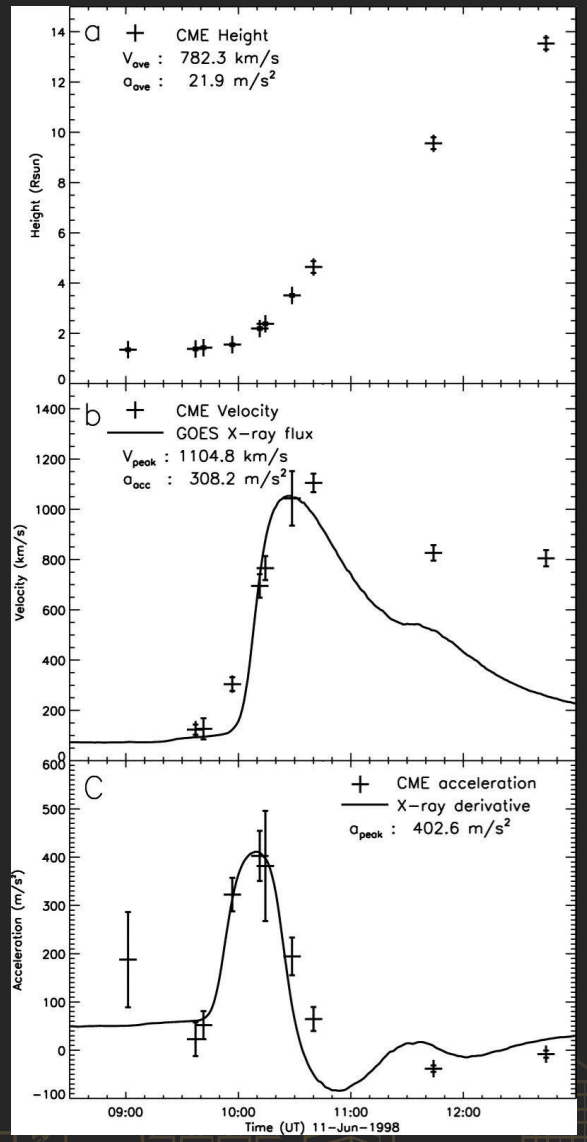
Gosling, J. T.

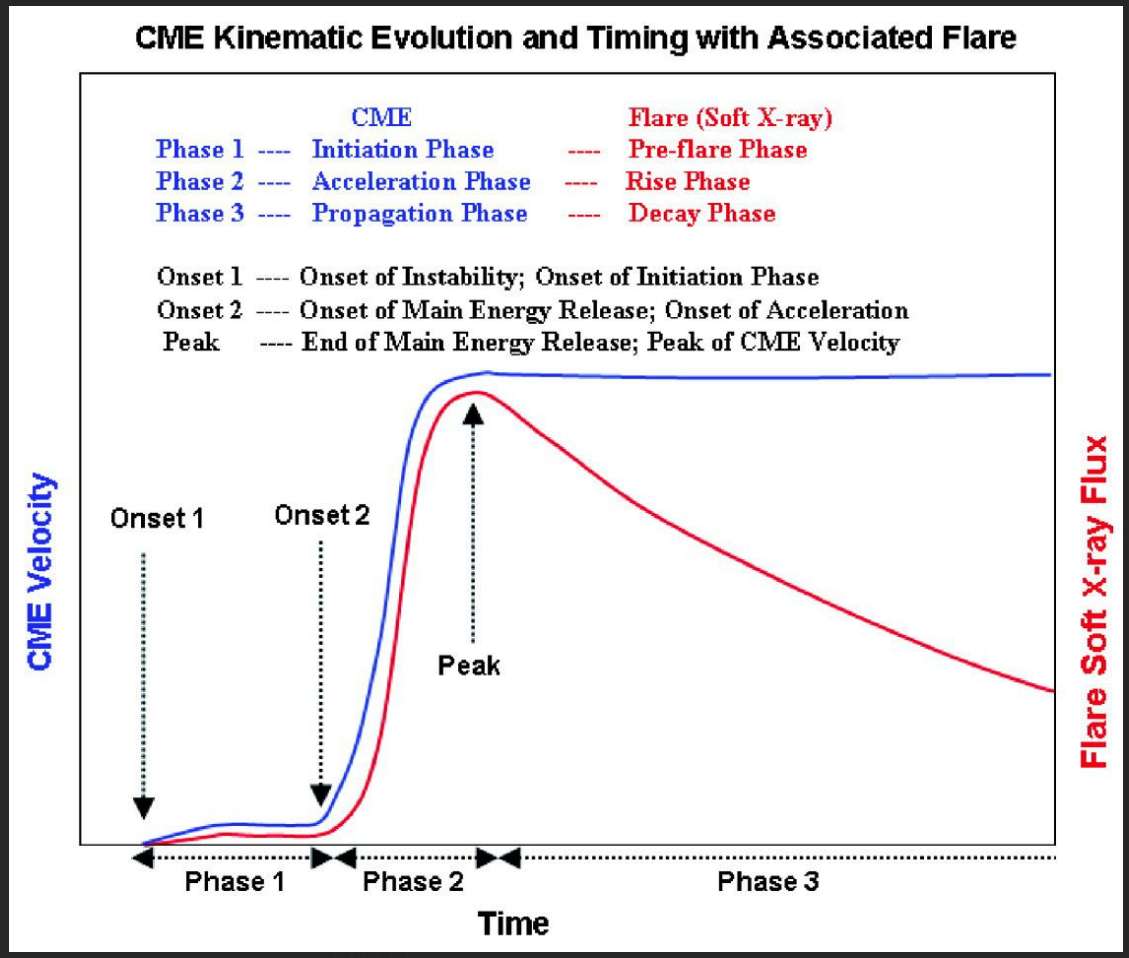
Many years of research have demonstrated that large, noncurrent geomagnetic storms, shock wave disturbances in the solar wind, and energetic particle events in interplanetary space often occur in close association with large solar flares. This result has led to a paradigm of cause and effect-that large solar flares are the fundamental cause of these events in the near-Earth space environment. This paradigm, which I call ``the solar flare myth,'' dominates the popular perception of the relationship between solar activity and interplanetary and geomagnetic events and has provided much of the pragmatic rationale for the study of the solar flare phenomenon. Yet there is good evidence that this paradigm is wrong and that flares do not generally play a central role in producing major transient disturbances in the near-Earth space environment. In this paper I outline a different paradigm of cause and effect that removes solar flares from their central position in the chain of events leading from the Sun to near-Earth space. Instead, this central role is given to events known as coronal mass ejections.

Publication: Journal of Geophysical Research, Volume 98, Issue A11, p. 18937-18950

Pub Date: November 1993

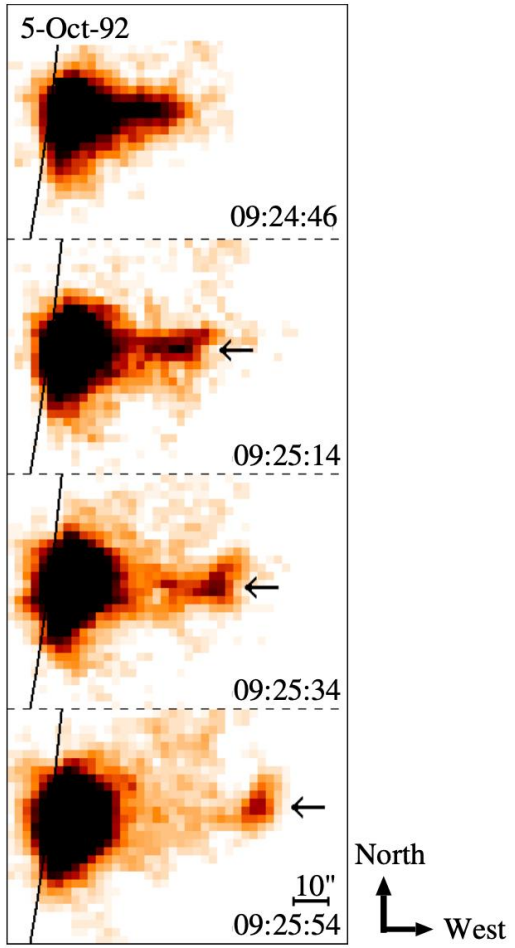
3. 磁通量绳的观测发现——CME和耀斑的关系

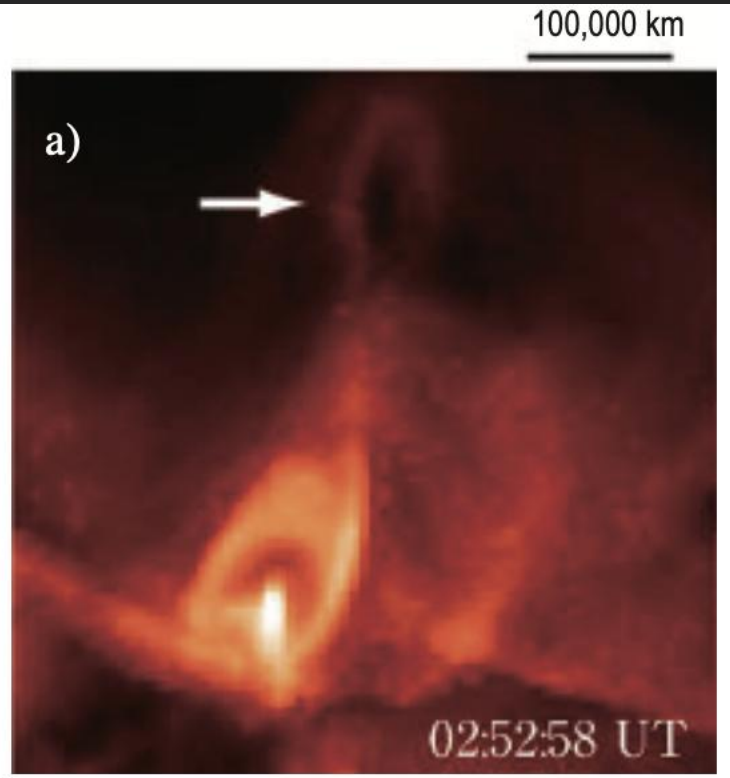




Zhang, J., Dere, K. P., Howard, et al. 2001, ApJ, 559, 452
Zhang, J., Dere, K. P., Howard, R. A., & Vourlidas, A. 2004, ApJ, 604, 420
Zhang, J., & Dere, K. P. 2006, ApJ, 649, 1100

3. 磁通量绳的观测发现——软X射线等离子体团





磁绳的观测特征是什么？

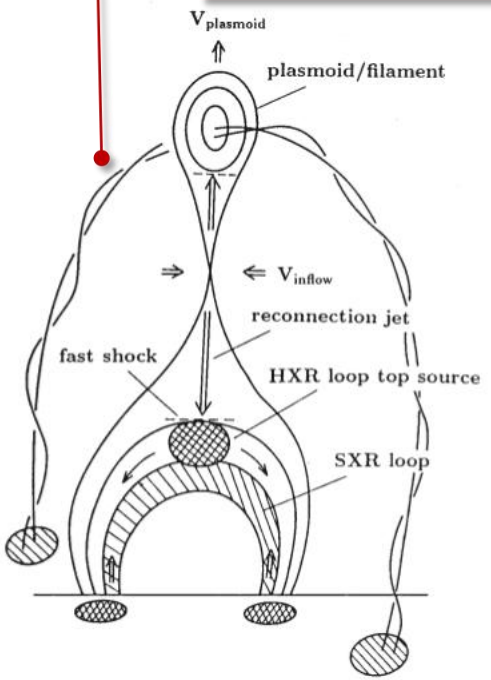
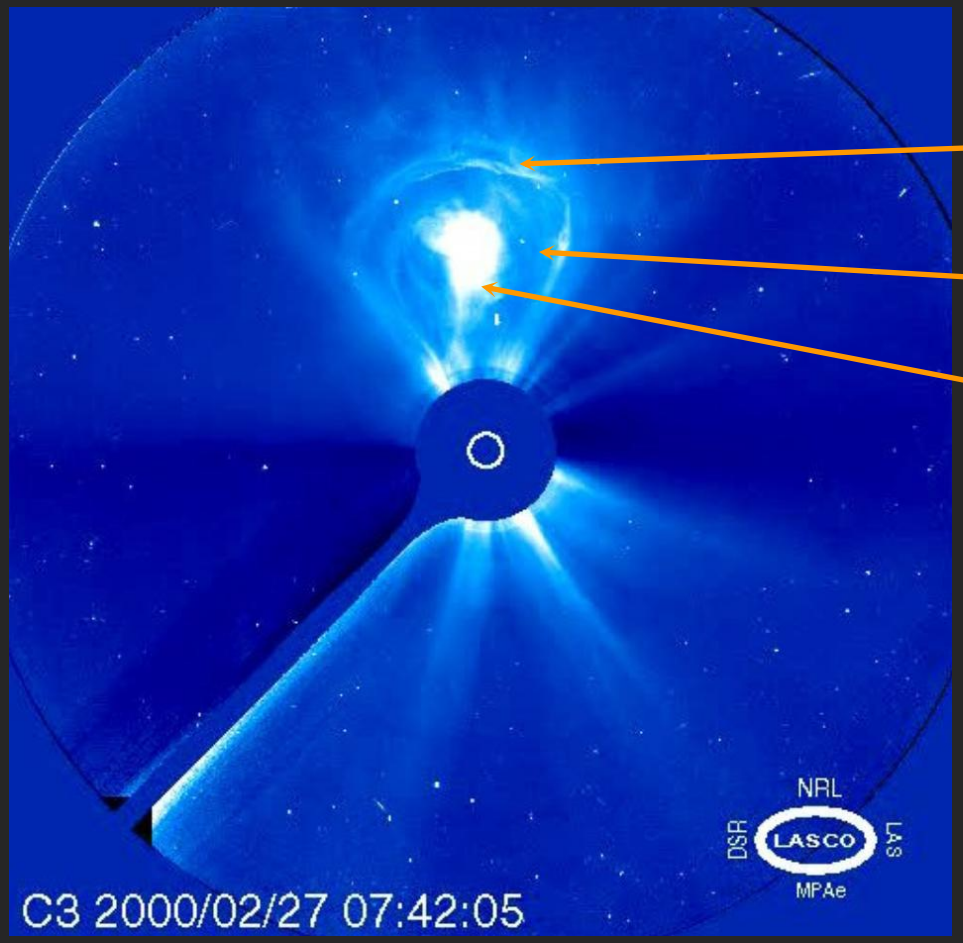


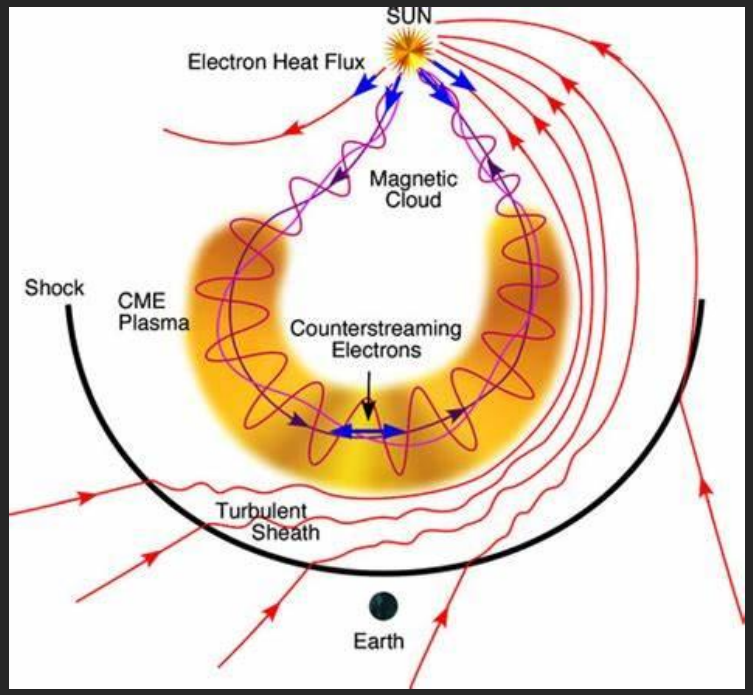
Figure 3: (a) Soft X-ray image of a *long-durational-event (LDE)* flare (see Section 2) observed by *Yohkoh*. (b) Schematic picture of a modified version of the CSHKP model, incorporating the new features discovered by *Yohkoh* (from Shibata *et al.*, 1995).

3. 磁通量绳的观测发现——CME结构

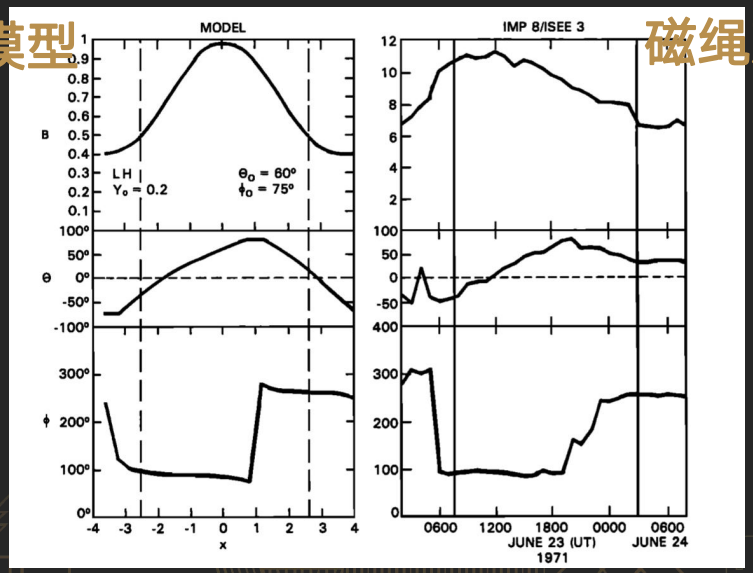


亮前沿
（背景等离子体堆积）
暗腔
（磁绳）
亮核
（稠密等离子体）

(Chen 2011; Webb 2012)



磁绳模型



磁绳观测

(Burlaga 1988)

3. 磁通量绳的观测发现——热通道/等离子体泡

THE ASTROPHYSICAL JOURNAL LETTERS, 732:L25 (6pp), 2011 May 10 doi:10.1088/2041-8205/732/2/L25

OBSERVING FLUX ROPE FORMATION DURING THE IMPULSIVE PHASE OF A SOLAR ERUPTION

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ARTICLE

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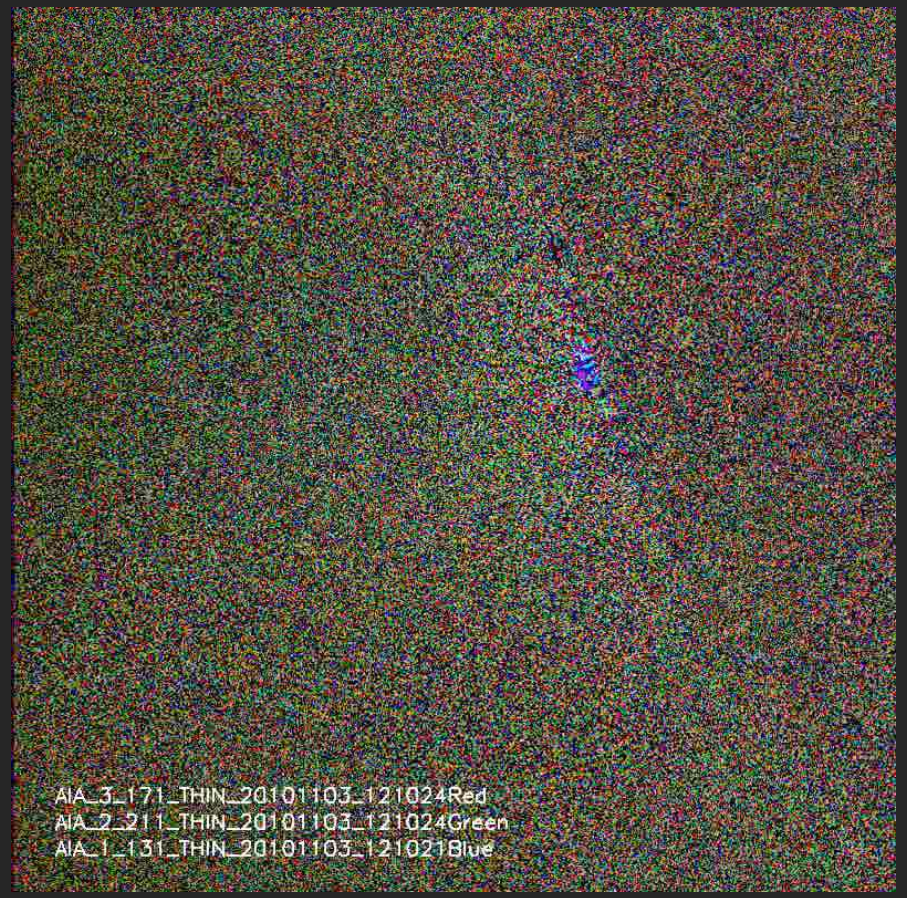
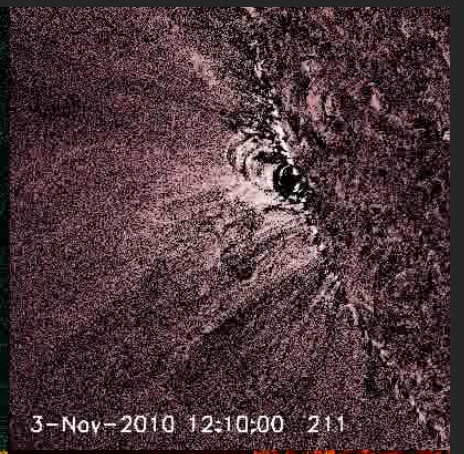
DOI: 10.1038/ncomms1753

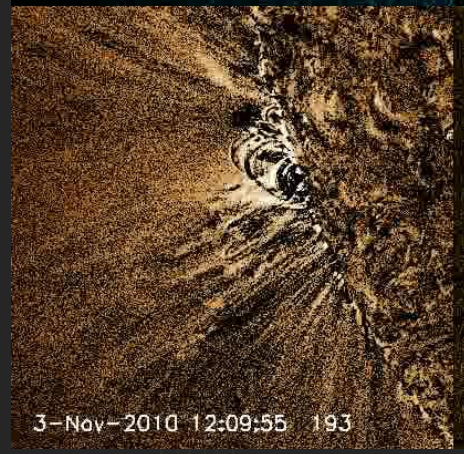
Observation of an evolving magnetic flux rope before and during a solar eruption

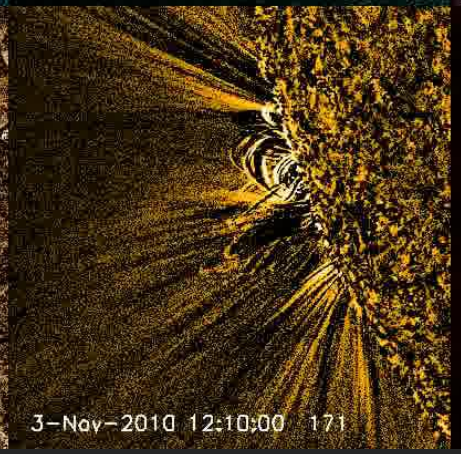
Jie Zhang[1], Xin Cheng[1,2] & Ming-de Ding[2]

3. 磁通量绳的观测发现——热通道/等离子体泡

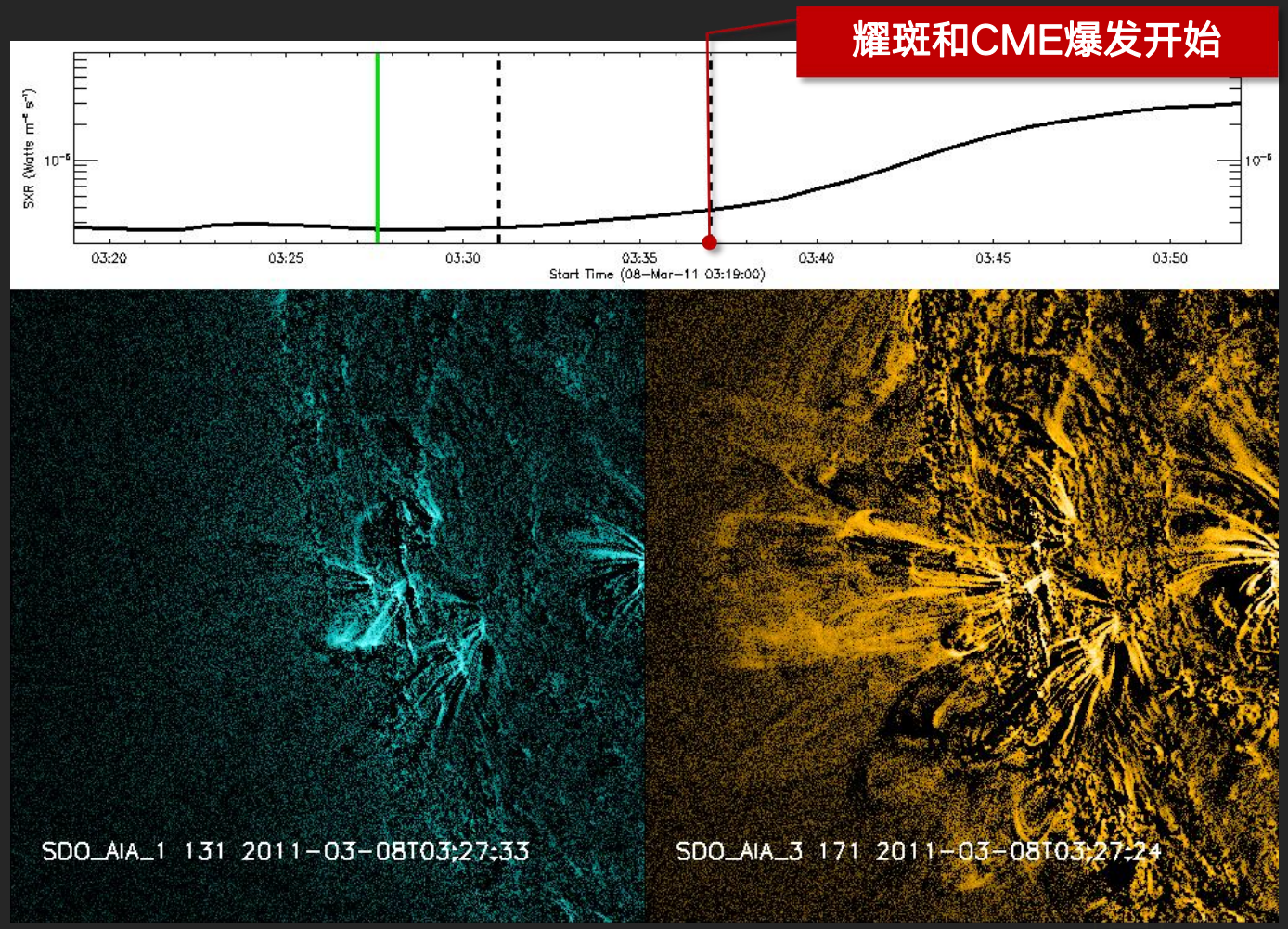


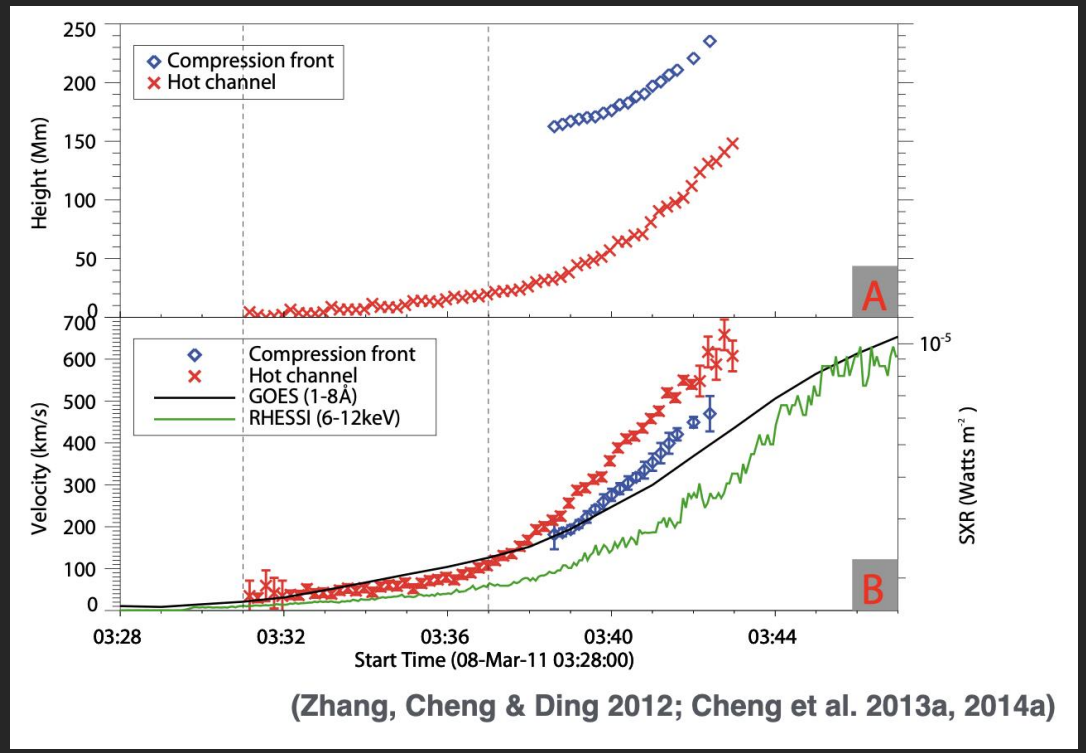






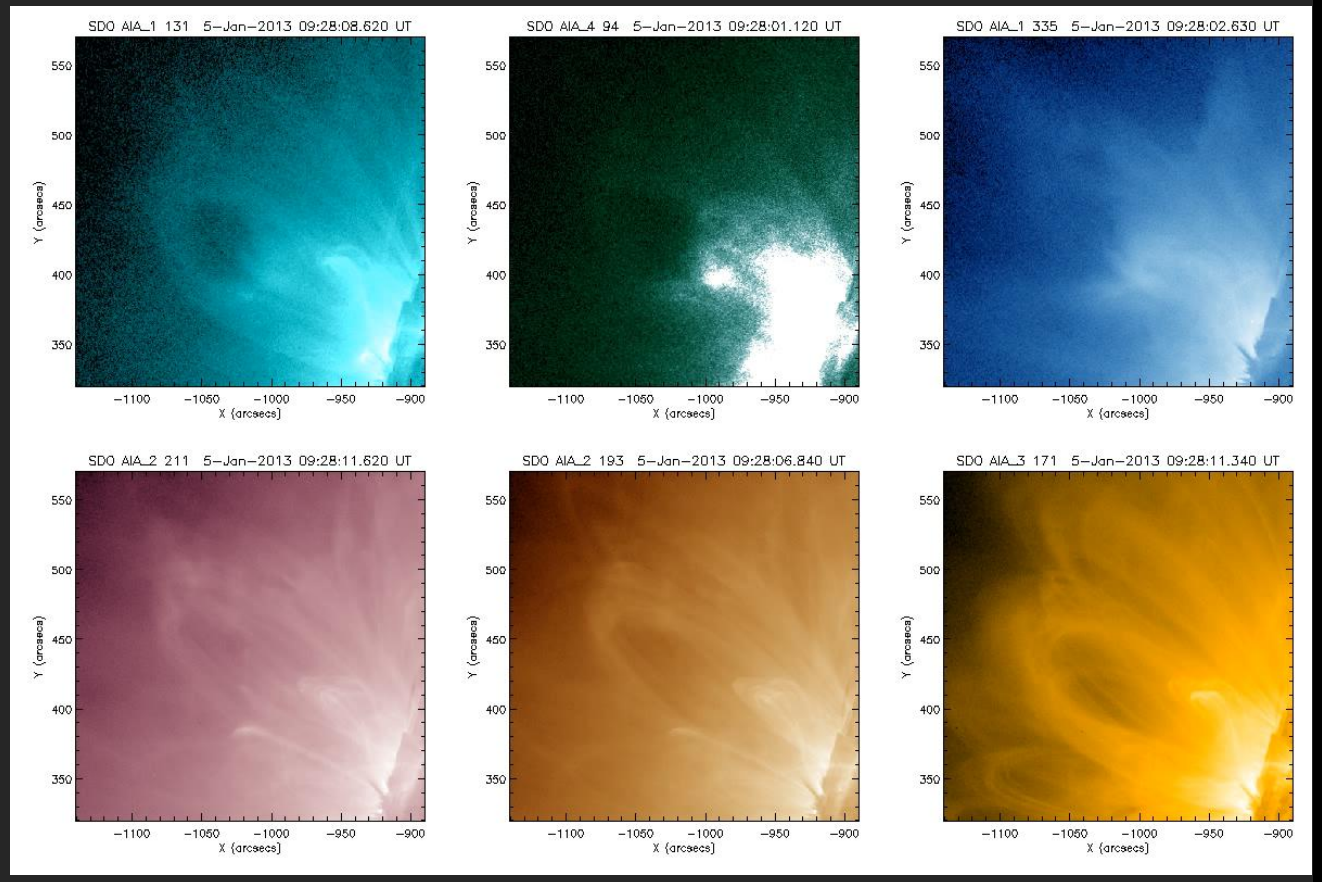
3. 磁通量绳的观测发现——热通道/等离子体泡

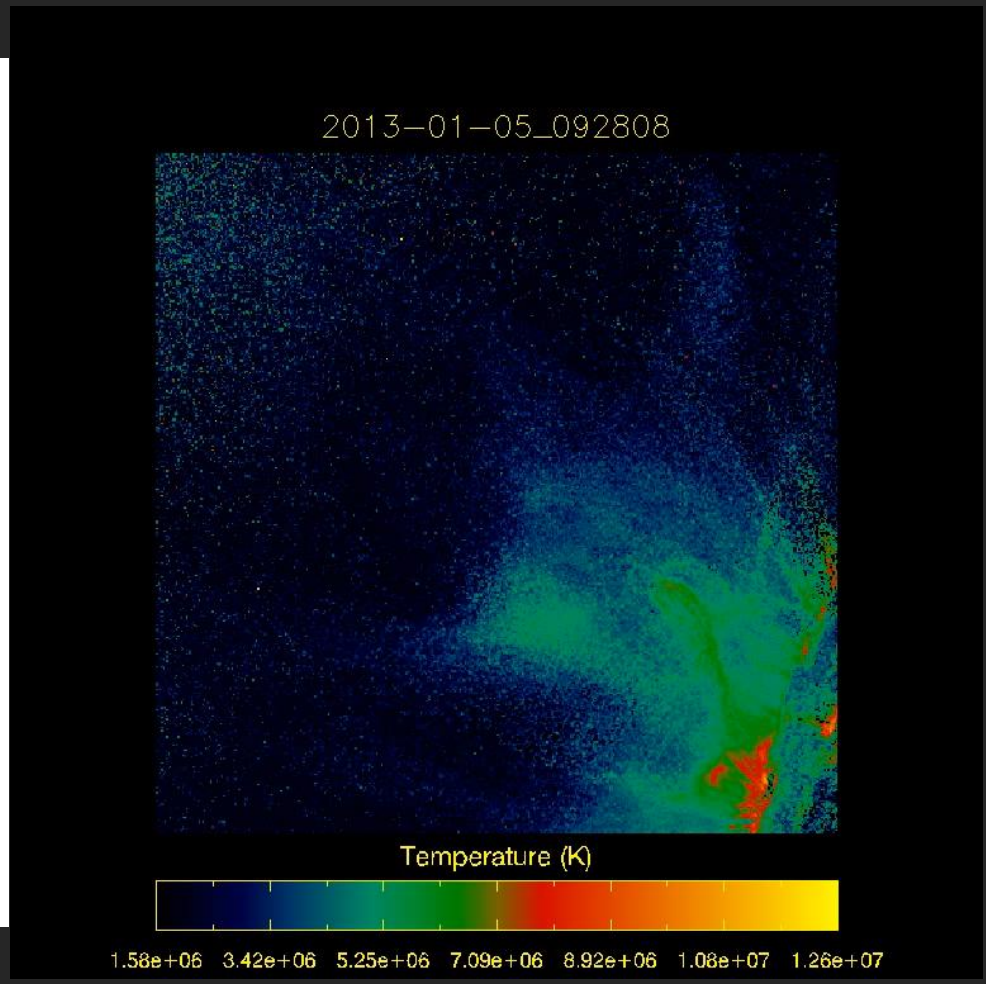




(Zhang, Cheng & Ding 2012; Cheng et al. 2013a, 2014a)

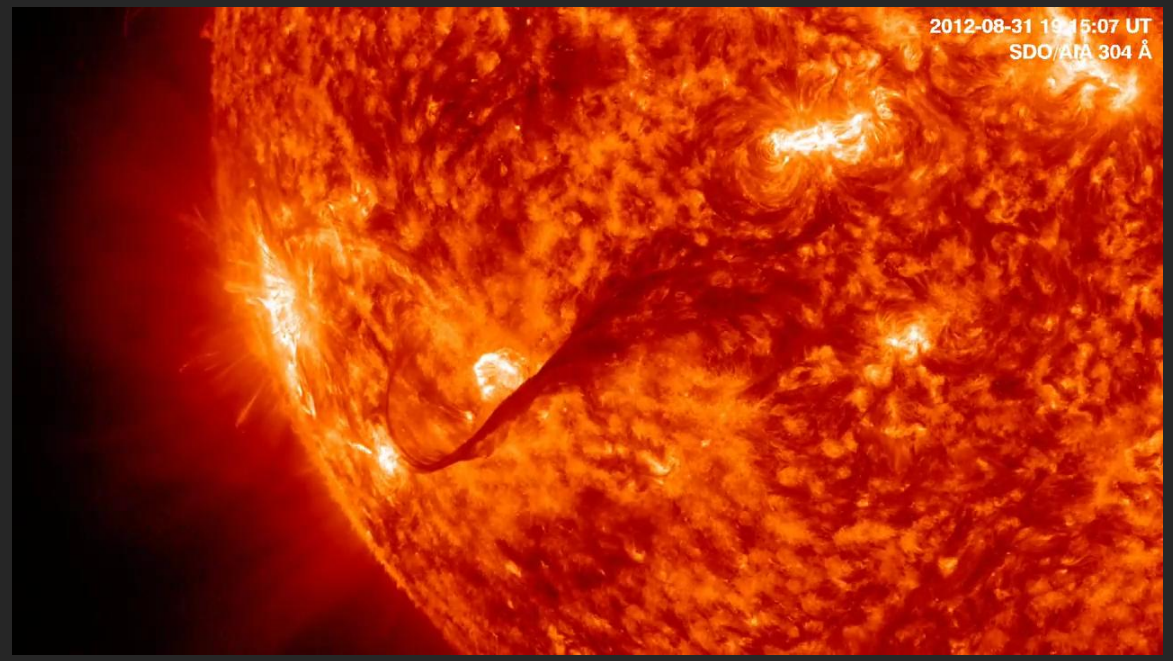
3. 磁通量绳的观测发现——失败的热等离子体泡

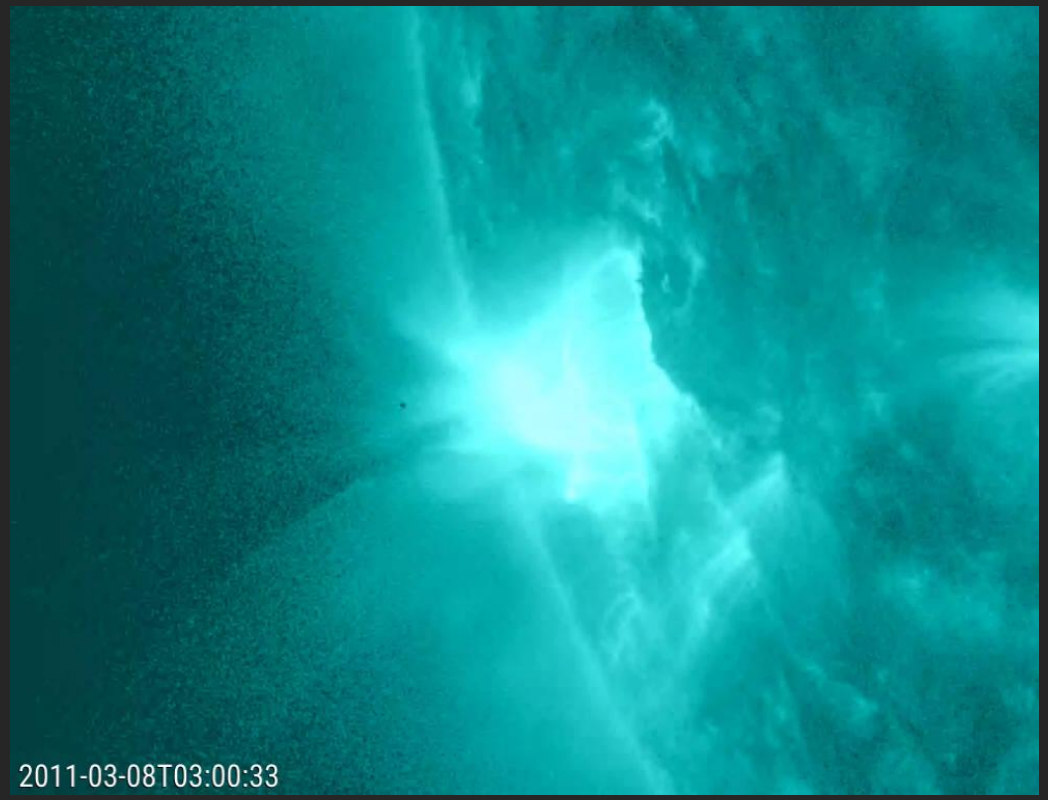




(Song et al. 2014)

3. 磁通量绳的观测发现——“冷”和“热”磁绳



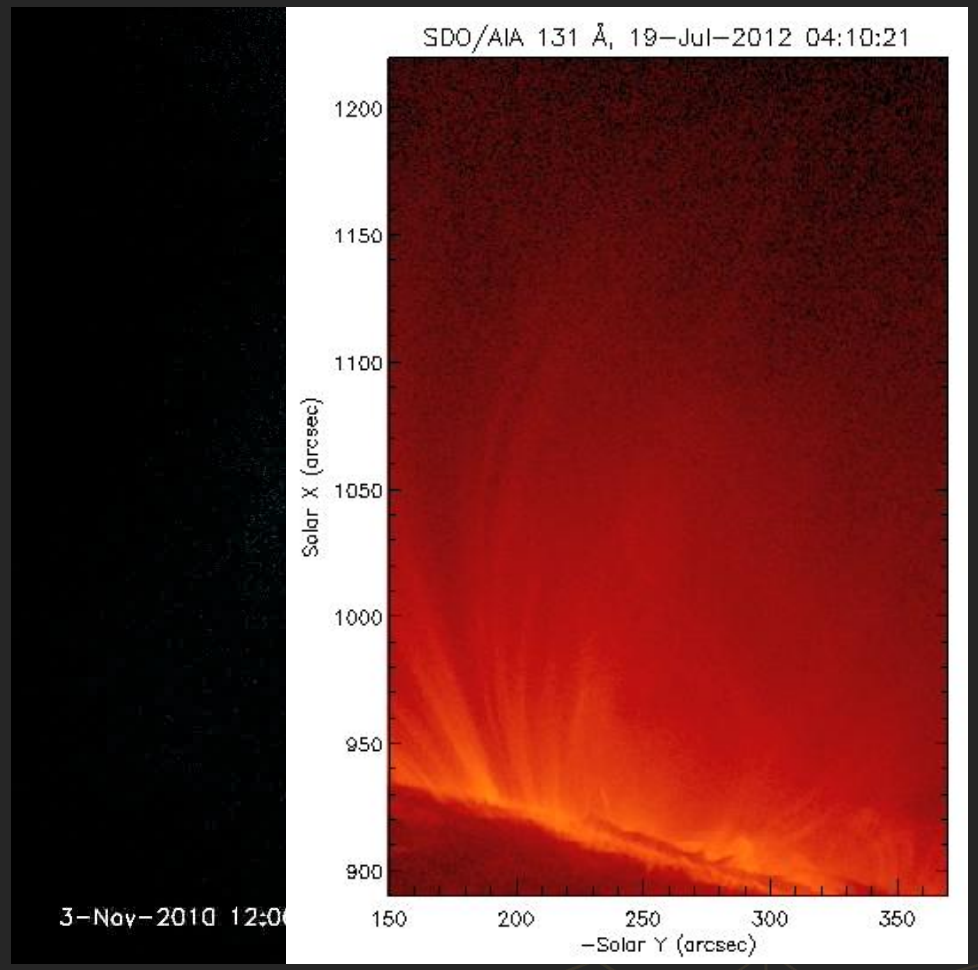


Filaments: Collection of cool and dense plasma in the hot and low-density corona.

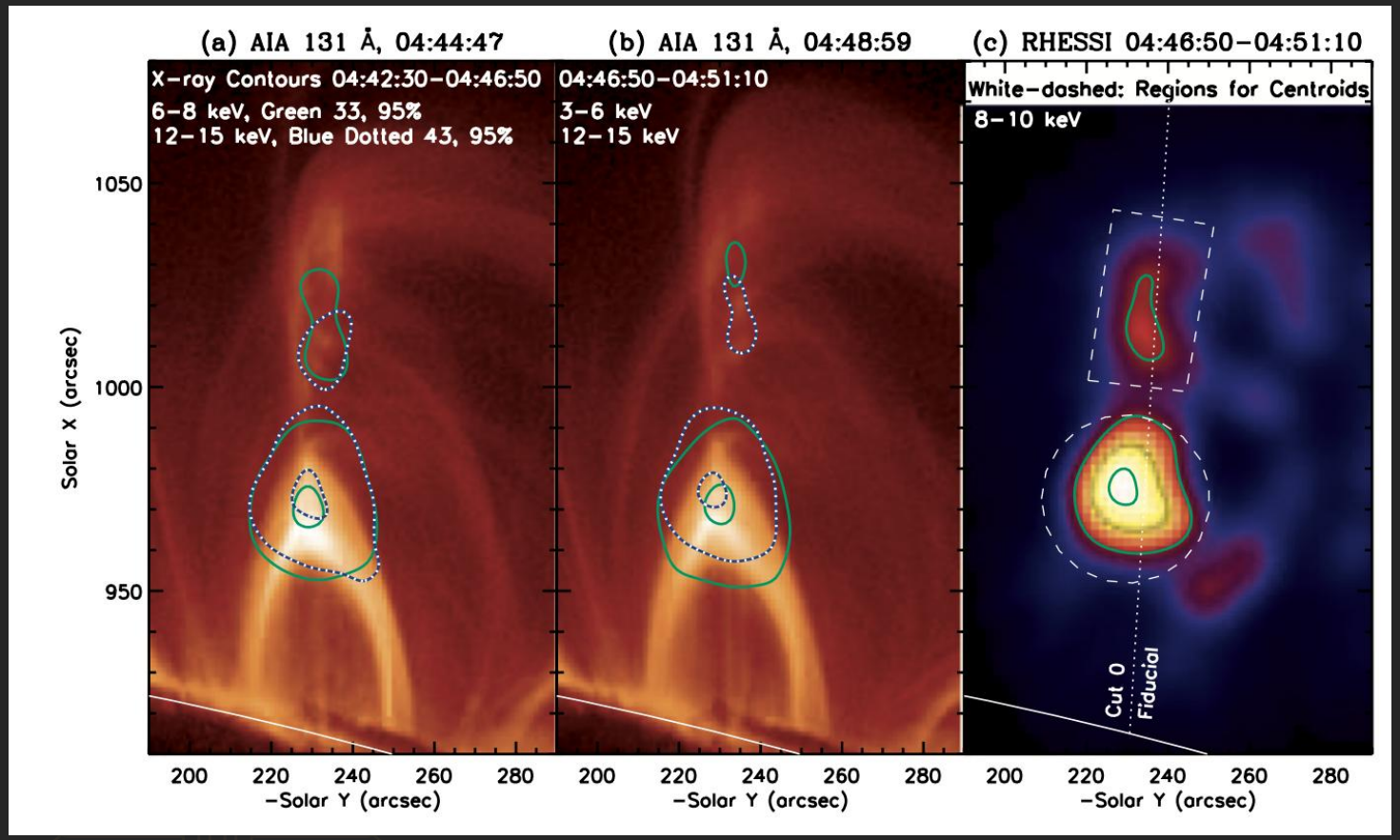
Hot Channel: EUV high temperature coherent structure in the AIA 131 and 94 passbands.

(Cheng+2011; Zhang+2012, 2015; Li+2013a, 2013b; Cheng+2013; Patsourakos+2013, Tripathi+2013; Dudík+2014; Chintzoglou+2015; Joshi+2015; Nindos+2015……)

3. 热磁通量绳的观测发现——热通道/等离子体泡/硬X射线辐射

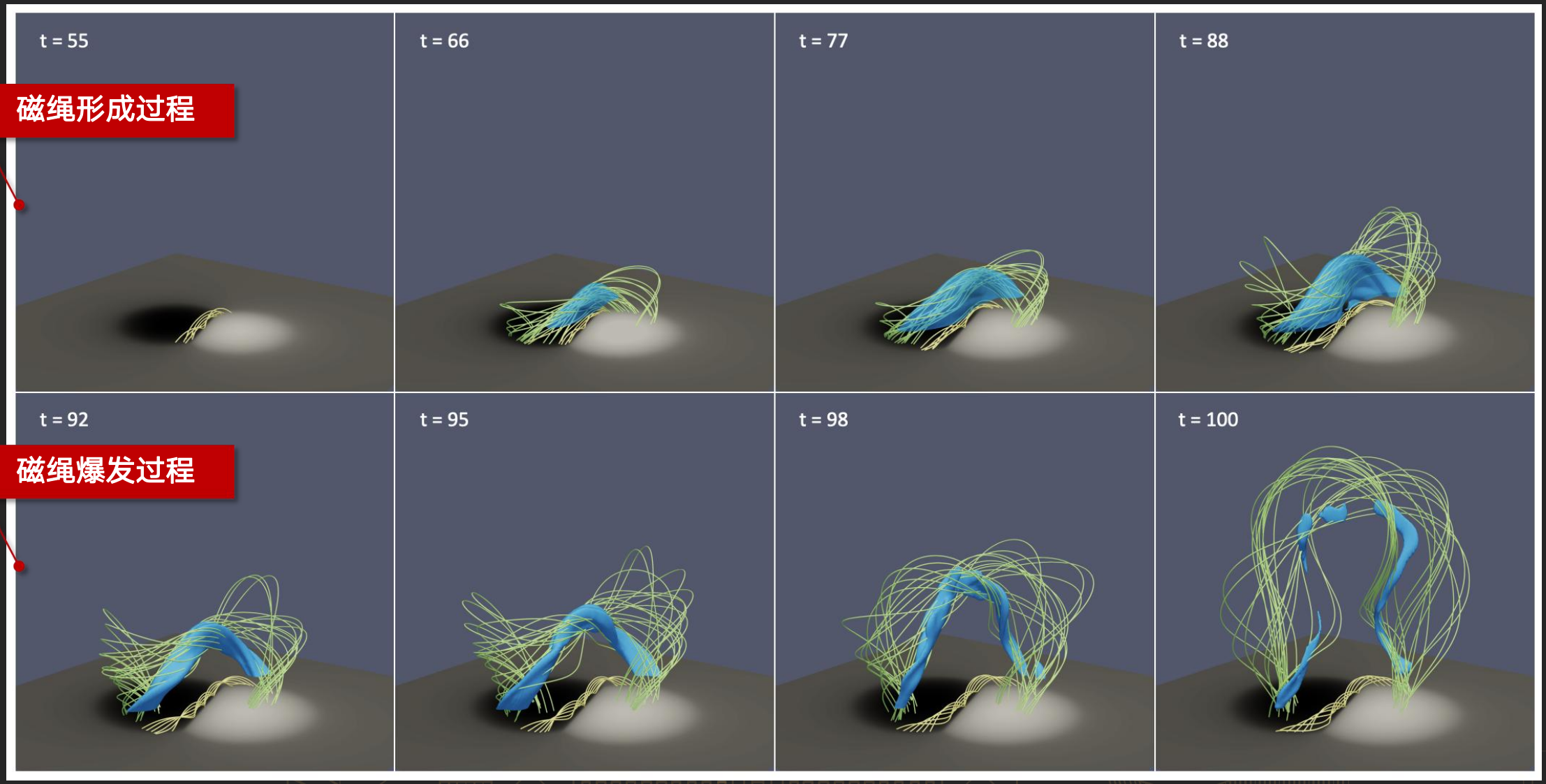


(Cheng et al. 2011 ApJL)



(Liu et al. 2013 ApJ)

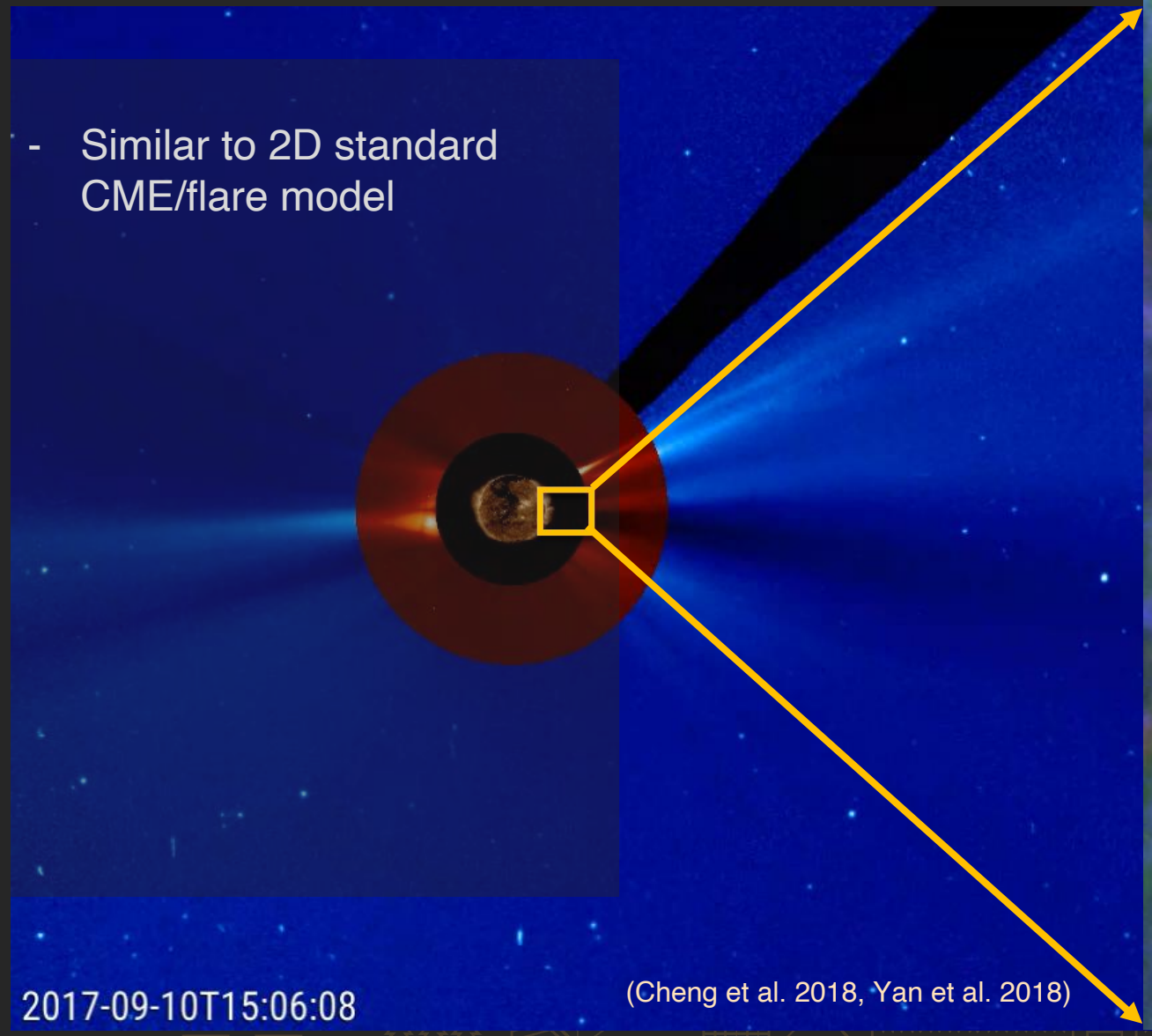
3. 热磁通量绳的观测发现——冷热磁绳的统一模型



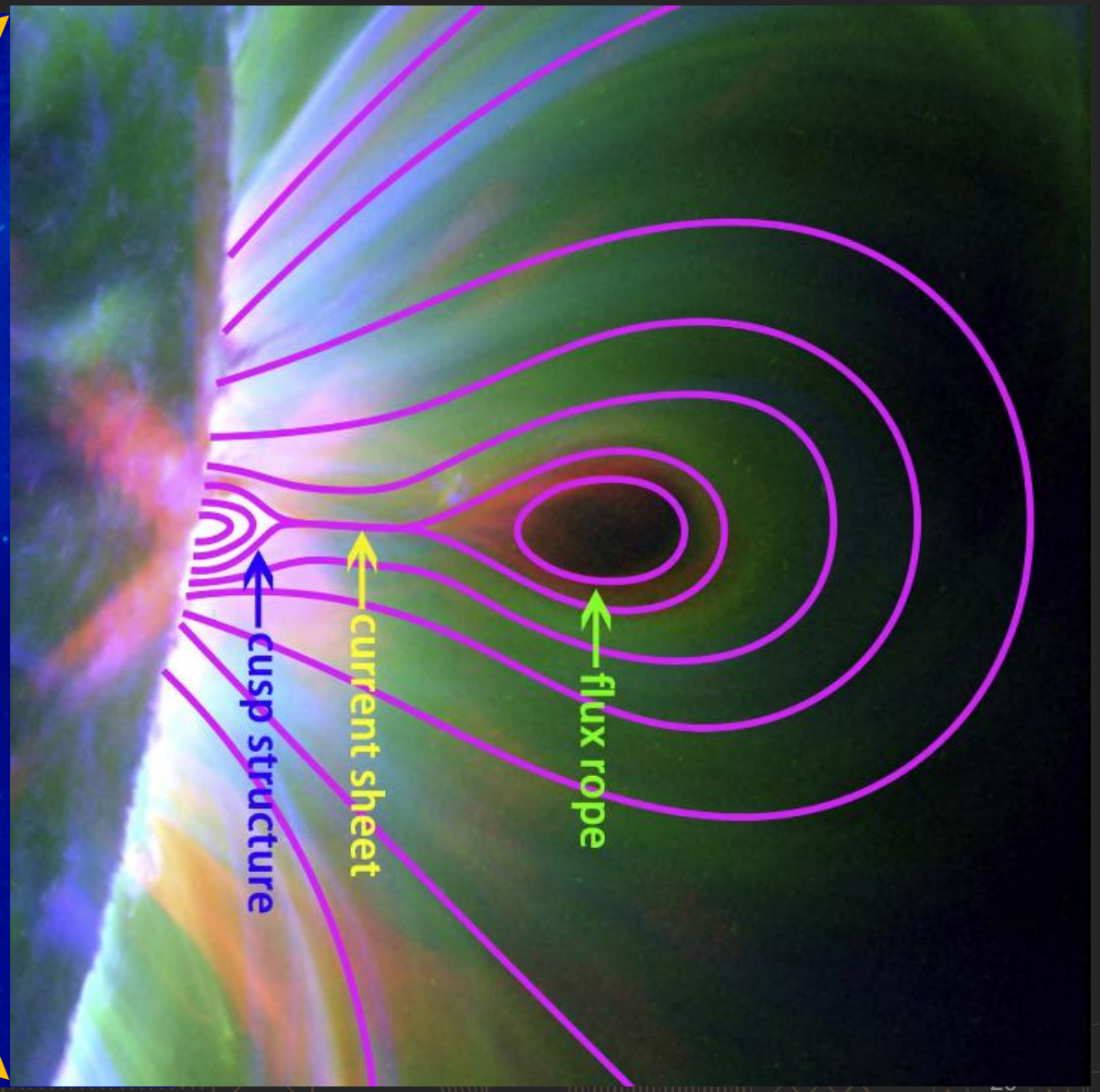
(Xing, Cheng et al. 2025)

3. 热磁通量绳的观测发现——CME、耀斑、重联电流片

- Similar to 2D standard CME/flare model

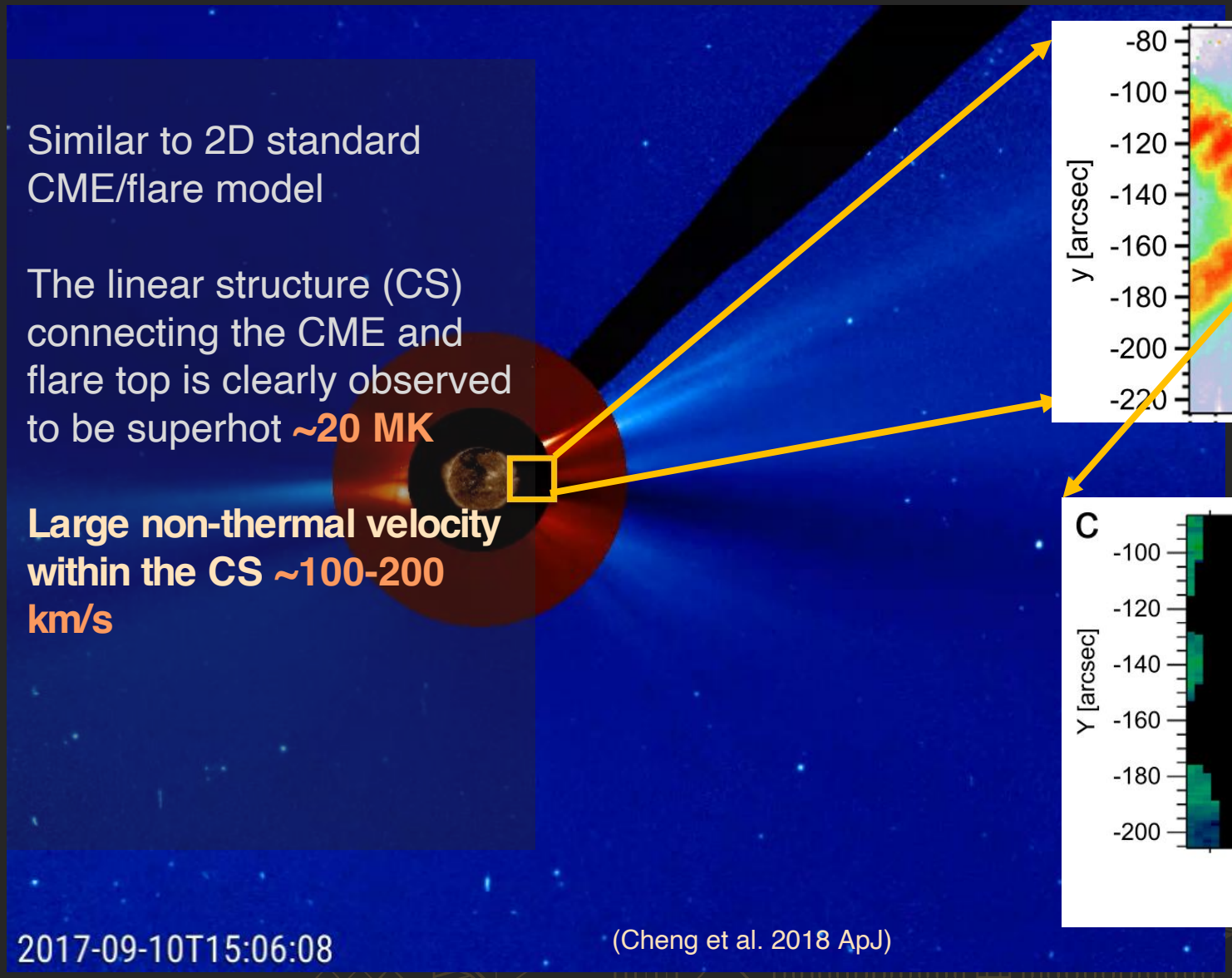


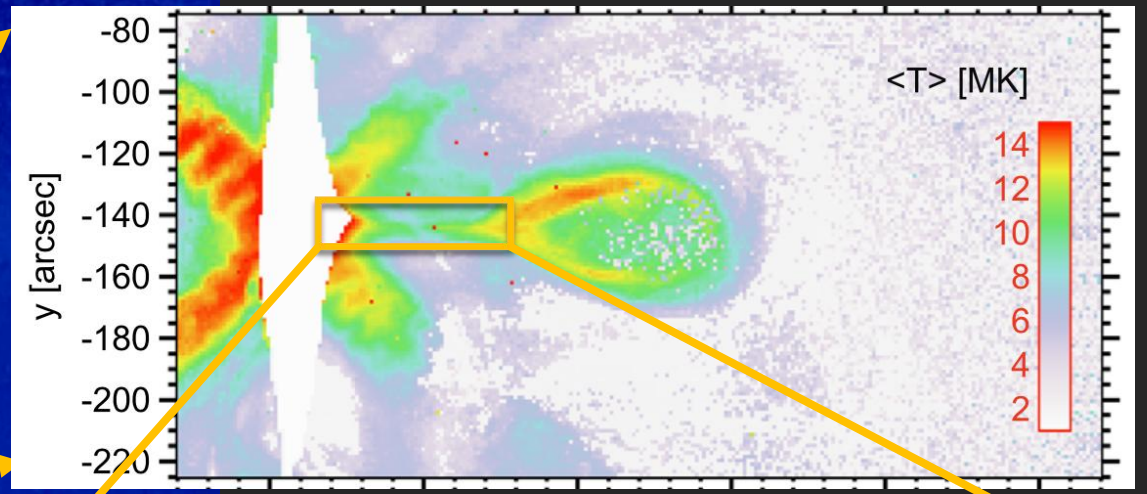
(Cheng et al. 2018, Yan et al. 2018)

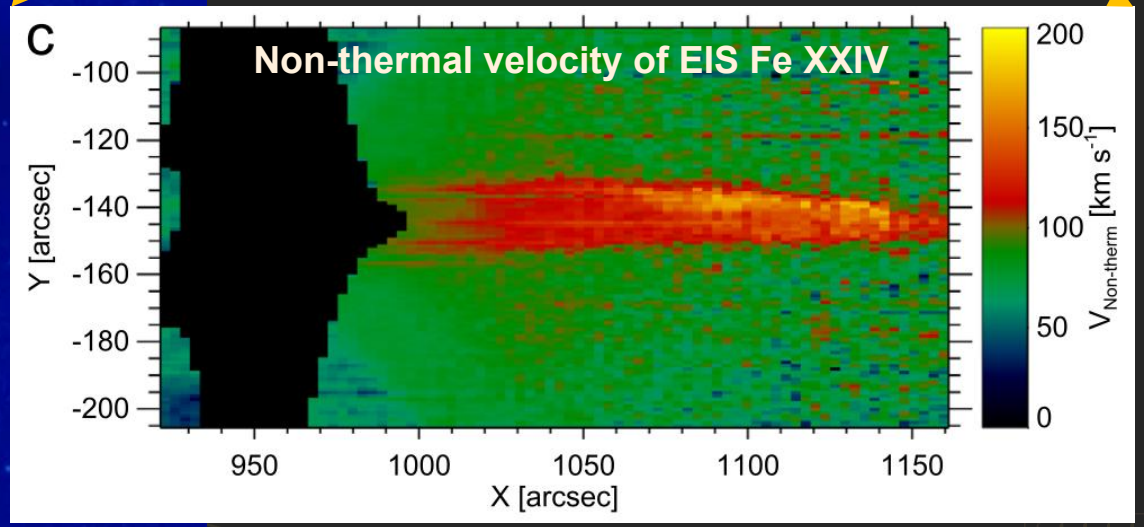


3. 热磁通量绳的观测发现——CME、耀斑、重联电流片

- Similar to 2D standard CME/flare model
- The linear structure (CS) connecting the CME and flare top is clearly observed to be superhot **~20 MK**
- **Large non-thermal velocity within the CS ~100-200 km/s**

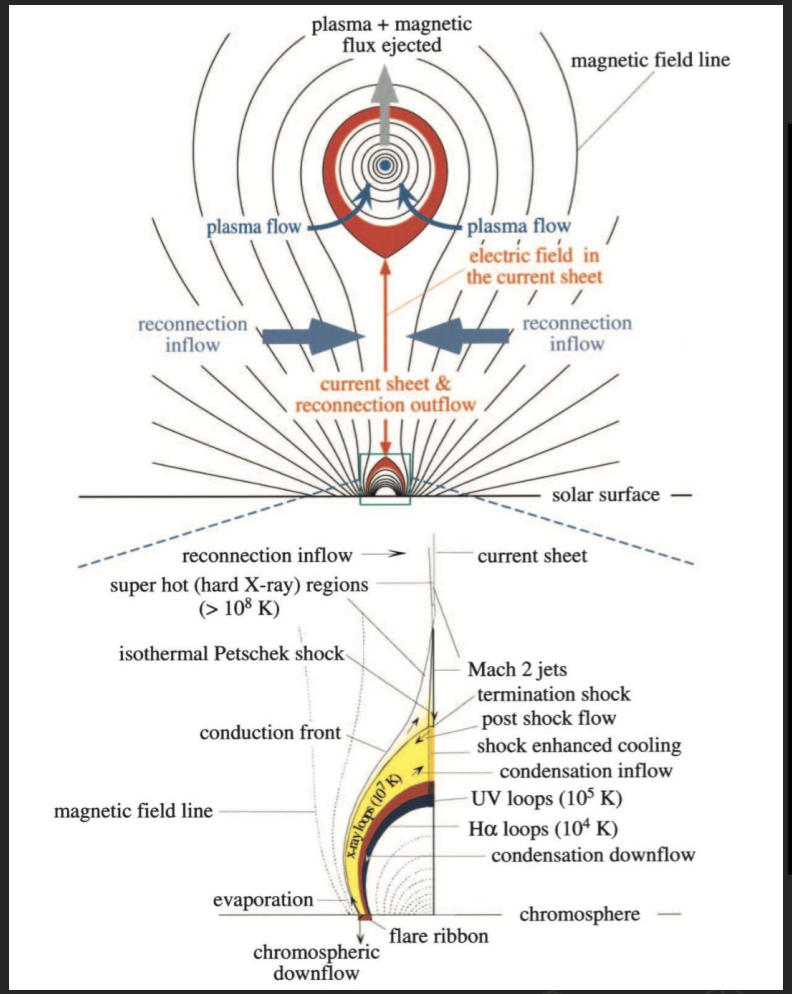




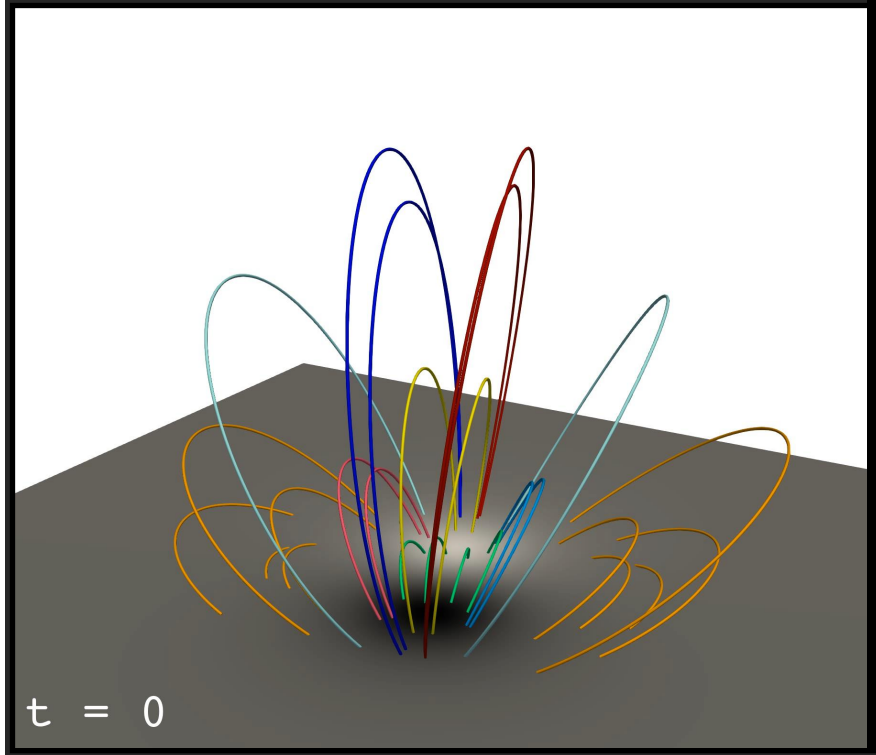


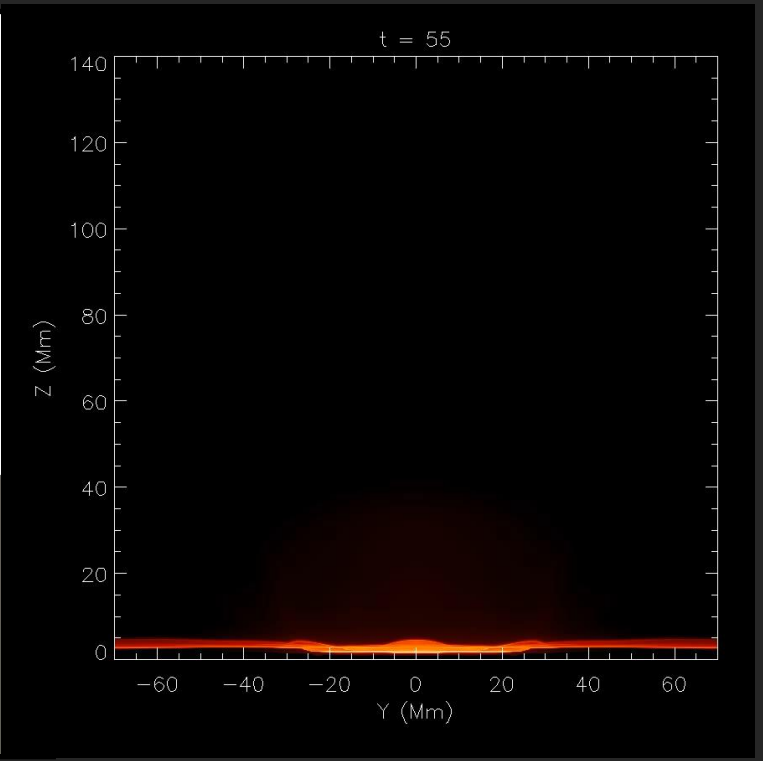
(Cheng et al. 2018 ApJ)

3. 热磁通量绳的观测发现——CME/耀斑标准二维、三维模型

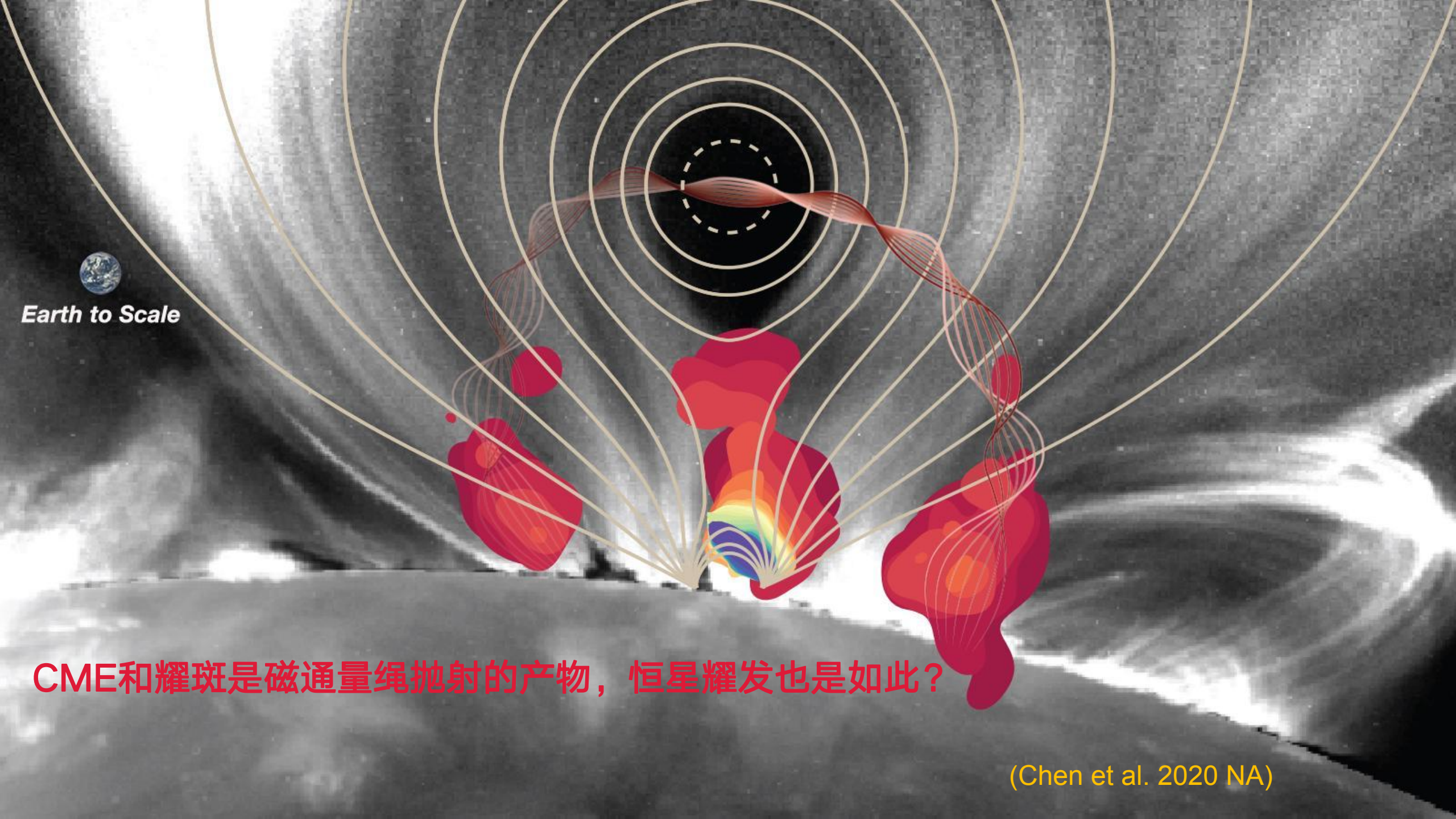


(Lin & Forbes 2000)





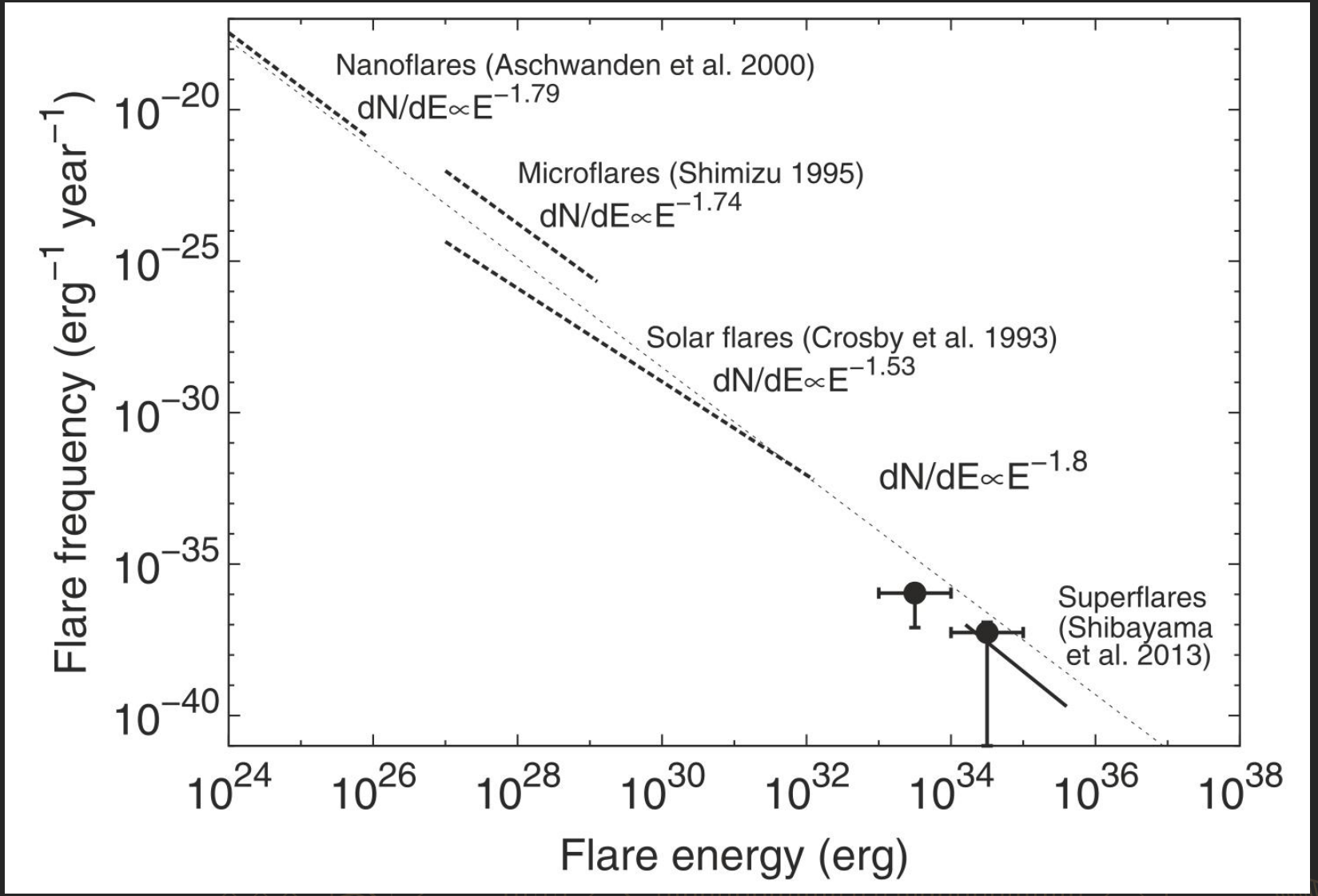
(Xing, Cheng et al. 2025)



CME和耀斑是磁通量绳抛射的产物，恒星耀发也是如此？

(Chen et al. 2020 NA)

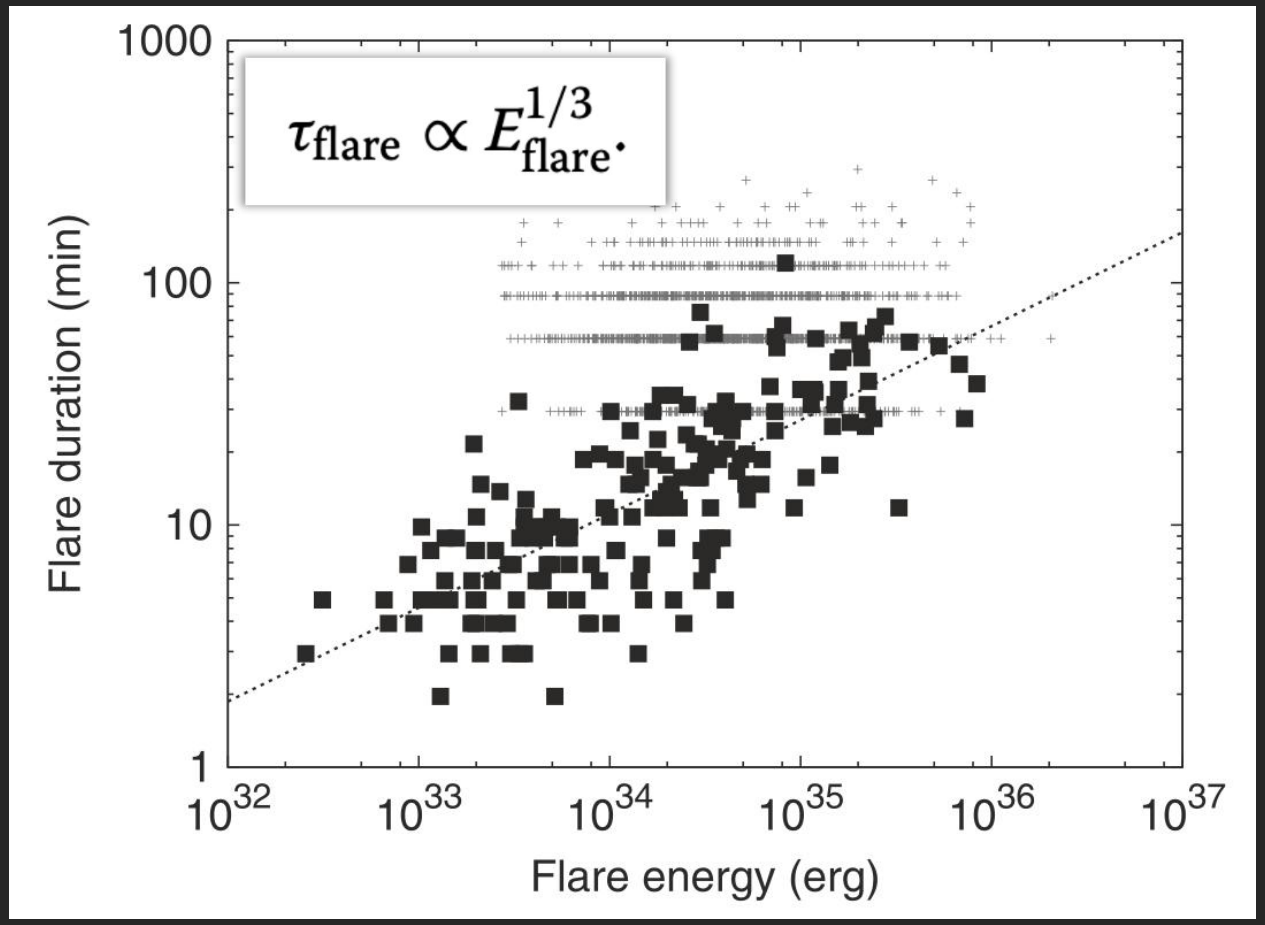
4. 标准CME/耀斑模型的启示——磁重联理论



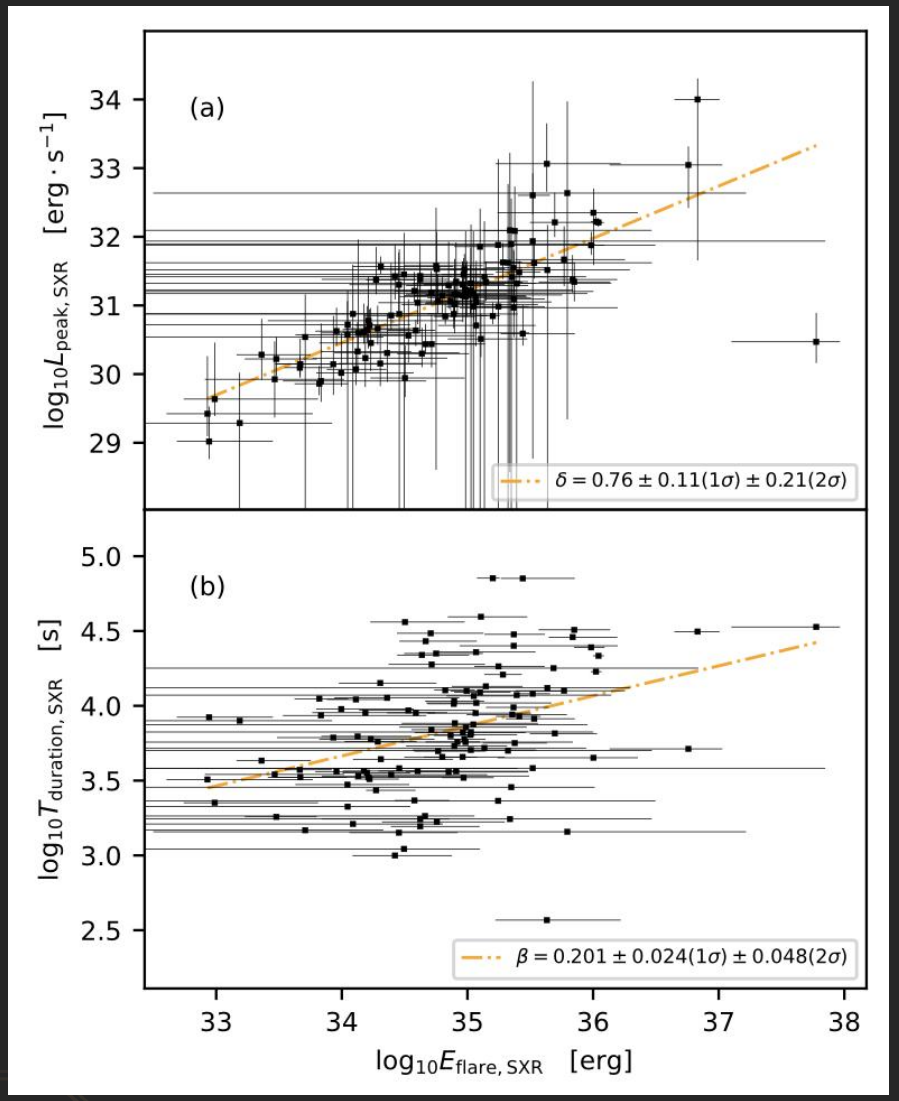
- 物理过程可能相同

- 磁场结构可能不同
- 驱动机制可能不同

4. 标准CME/耀斑模型的启示——T vs E



(Maehara et al. 2015)



(Zhao et al. 2024)

结论

1. 磁通量绳（暗条或热通道）是产生CME和耀斑的基本结构；
2. 磁重联是加速CME抛射和产生耀斑辐射的关键机制；
3. CME耀斑模型也适用于恒星耀发过程。

Thanks!