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太阳耀斑研究的新进展

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摘　要

近年来对太阳耀斑的研究取得了重要的进展。一些新的发现主要来自高分辨率的观测，特别是来自"阳光"卫星的结果。综述的范围包括太阳耀斑中磁重联的新证据、硬 X 射线源 (包括所谓的超热源) 的分类、X 射线喷流的发现、环 — 环相互作用的证据以及对耀斑大气动力学过程的新认识等。基于这些新的知识，讨论了有关耀斑模型的一些问题。

关 键 词　空间飞行器 — 太阳：耀斑 — 方法：观测

Recent Progress in the Study of Solar Flares

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Abstract

In recent years, important progress in the study of solar flares has been achieved. Some new discoveries come mainly from high resolution observations, especially from the Yohkoh satellite. The scope of this review involves new evidence of magnetic reconnection in solar flares, the classification of hard X-ray sources (including so-called superhot sources). the discovery of X-ray jets, evidence for loop-loop interactions, and new knowledge of the hydrodynamic process of flare atmosphere, etc. Based on the new information, some aspects of flare modelling are also discussed.

Key words space vehicles—Sun: flares—methods: observation

1 Introduction

Observations are always an original motive power for the study of solar physics. During the

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past solar cycle No.22, many high resolution observations were done both from space and ground, from γ and X-ray to radio domain. Recent progress in the study of solar flares concentrates mainly in the new observations, though there are also some developments of theoretical work. In the space observations, the most spectacular results come from the Yohkoh satellite. It carries four types of dedicated instruments [1]: the soft X-ray telescope (SXT, see [2]), the Bragg crystal spectrometer (BCS, see [3]), the hard X-ray telescope (HXT, see [4]), and the hard X-ray and γ-ray spectrometer , two constituents of the wide-band spectrometer (WBS, see [5]). As concerns the ground-based observations, the following instruments should be mentioned: the Nobeyama Radioheliograph, two dimensional (imaging) spectrographs (see [6] for a review), high-resolution magnetographs, multichannel subtractive double pass (MSDP) spectrographs, high temporal resolution radio telescopes, as well as many telescopes giving Hα and white-light images with good quality.

These observations, both from space and ground, give us not only much more detailed pictures of solar flare process, but also many discoveries of new aspects of flares. This paper will describe some recent progress in the study of solar flares, mainly in point of observations. Some related theoretical work will also be mentioned. Many interesting details of new advancement are summarized in several recent proceedings [7–11] for reference.

2 New Progress in the Study of Flares

In recent years, some new progress in the study of solar flares has been achieved both from observation and theoretical work, but mainly due to some new discoveries in the observations. The most exciting progress is probably in the following six aspects:

2.1 New evidence for magnetic reconnection in solar flares

Solar flares are thought to be the result of magnetic reconnection, i.e., the merging of antiparallel magnetic fields, which results in the release of magnetic energy. Recent Yohkoh observations [12,13] supported the point of view that a two-ribbon flare relates to the eruption of a solar prominence, that pulls magnetic field lines upward, forming an inverted Y-shaped structure and then the reconnection takes place. Soft X-ray observations showed [14] that several hours prior to the flare of 21 February 1992, there was a "helmet streamer" arch, which expanded and made the flare triggered. The main loop structure continuously increased in its height and the footpoints separated at a velocity of 10–30 km $\cdot$s^{-1}. In the decay phase, the outer shell of the arch has a higher temperature and the temperature decreases toward the inner arch. All these suggest that an X-type of reconnection point was formed at the top of the arch, and the current sheet is the primary energy source.

As concerns the impulsive compact flares, Yohkoh observations show also strong evidence for magnetic reconnections. Masuda [15] analysed ten limb flares and found that six ones among them showed loop-top hard X-ray sources. The most typical one is the flare on 13 January 1992 [16]. Figure 1 shows its hard X-ray and soft X-ray images in the impulsive phase of the flare. The temperature and the emission measure distributions are also shown in the figure.

It can be seen that except the double footpoint sources seen in the hard X-ray, a loop-top hard X-ray source only appeared for a short time interval. If the X-ray emission from the source is interpreted as thermal bremsstrahlung, the electron temperature would be about 2 × 10^8 K. Masuda *et al.*[16] proposed a hypothetical scenario, in which an outflow or jet from the reconnection point impinges on the underlying closed loop and forms a shock, resulting in a high-temperature region just above the closed loop. It is also likely that electrons are accelerated in the shock and stream down along the reconnected field, forming the double footpoint sources. However, Wheatland and Melrose [17] suggested that the high-temperature region is formed by the bombardment of electron beam which comes from the reconnection region. Anyway, these observations provide strong evidence to indicate that the flare energy comes from reconnection points and where an outflow or jet and/or an accelerated electron beam appears, going down to the loop-top and heating the flare loops.

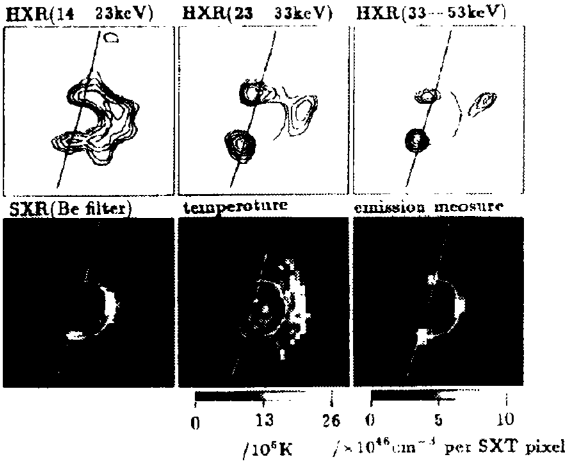

Fig.1 Hard X-ray (top) and soft X-ray (bottom) images of 13 January 1992 flare. Contour levels for the HXT energy bands are 70.7, 50.0, 35.4, 25.0 and 17.7 % of the peak intensity for each map. The field of view of each frame covers 78.4 × 78.4 arcsec.[16]

2.2 Classification of hard X-ray sources

Yohkoh observations revealed that several different types of hard X-ray sources exist in solar flares. Kosugi [18] presented a comprehensive review on the new results from Yohkoh. It indicated that there are mainly five types of hard X-ray sources:

(1) Double-footpoint sources in the impulsive phase. This is one of the fundamental characteristics of impulsive flares. Sakao *et al.*[19] have revealed, in the case of the white-light flare (WLF) of 15 November 1991, two sources, located at both sides of a magnetic neutral line, which are the most pronounced at X-ray energies $\geq$ 30 keV. The fact that the WLF kernels coincide with the double sources strongly supports the electron-precipitation interpretation. A systematic increase of the separation between the double sources was also found in this flare. Sakao *et al.*[20] analysed 28 flares having the peak count rates in the 33–53 keV band of ≥ 30 cts·$s^{-1} \cdot sc^{-1}$, and found : (a) the double-source structure can be found in $\sim$ 40% of the events; (b) the double sources simultaneously vary in intensity with time lags less than a fraction of a second; (c) the brighter source with a harder X-ray spectrum tends to correspond to a footpoint where the photospheric magnetic field is the weaker. These findings suggest that electrons are accelerated near the apex of flaring loops and then precipitate into the two footpoints in preference to the weaker magnetic field footpoint.

(2) Loop-top sources in the impulsive phase. As Figure 1 shows, these sources are much weaker in comparison with the double footpoint sources, but their intensities vary impulsively and similarly to the footpoint sources. It is thought that this type of hard X-ray sources gives evidence for magnetic reconnection which is under progress above the source and resulting in particle accelerations.

(3) Loop-top sources in the gradual phase. Yohkoh HXT L-band (13.0–22.7 keV) observations show [21] that a gradually-varying source is often observed and usually located in between the double footpoint sources. This type of sources becomes pronounced after the impulsive phase. It has a steep hard X-ray spectrum which is typical for thermal emission from a plasma with temperature $T \simeq 2 \times 10^7 - 4 \times 10^7$ K and emission measure from 10^{46} to 10^{49} cm^{-3}. However, it is still not clear whether these sources are due to direct heating from energy release or due to evaporated plasma from the chromosphere. The observations seem still controversial [22,23].

(4) Super-hot thermal sources. They appear only rarely and characterize by the predominance of thermal emission from a plasma with $T \geq 3 \times 10^7$K. Thus, they are less efficient in particle acceleration. Kosugi *et al.*[24] analysed a typical flare of 6 February 1992 and found that the northern loop, flaring up some 10 minutes later, showed a gradual intensity peak lasting for longer than 10 minutes with temperature exceeding 3×10^7 K and lack of associated microwave burst. This type of sources appears generally in the so-called type A flare[25].

(5) Gradual hard X-ray sources. This type of events was classified as the type C flare [26] and is characterized by high altitude ($\sim 5 \times 10^4$ km) hard X-ray sources, gradually varying X-ray and microwave fluxes, as well as X-ray spectral hardening with time. All these imply trapped nonthermal electrons and/or continuous acceleration. Up to now, only few examples showing some properties of this type of flares have been detected by Yohkoh.

2.3 Discovery of X-ray jets

Among various coronal dynamical phenomena, one of the most surprising findings is coronal X-ray jets [27,28]. They are defined as transitory X-ray enhancement with an apparent collimated motion. Most of jets are associated with small flares or loop brightenings. Some jets ejected from X-ray bright points (XBPs) in coronal holes or quiet regions, Emerging Flux Region (EFRs) and Active Regions (ARs). The jets ejected from XBP-like structures in ARs often correspond to satellite spots (or emerging fluxes) and some of these jets coexist with Hα surges. The jets ejected from EFRs/ARs in coronal holes show often anemone-jet type [29], while the jets associated with EFRs/ARs in quiet regions show two-sided-loop (jet) type. Its brightening suddenly appears at both sides of EFRs/ARs along the nearly horizontal field. Figure 2 shows some typical examples of these types of jets.

Yokoyama and Shibata [30] performed a MHD numerical simulation for the reconnection between emerging flux and overlying coronal field. They found that the two-sided-loop type occurs when the coronal field is horizontal, and a pair of horizontal hot jets and cool magnetic island ejection are produced. The anemone-jet type occurs when the coronal field is vertical or oblique. It seems that the simulation can generally explain the observational properties of the jets.

Preliminary results show that the physical conditions of jets are as follows: length $\simeq 1 \times 10^4$–4×10^5 km, apparent velocity $\simeq$10–400 km s^{-1} in most cases, temperature $\simeq 2 \times 10^6 - 10^7$ K, electron density $\simeq 4 \times 10^8 - 3 \times 10^9$ cm^{-3}, mass $\simeq 10^{12} - 10^{14}$ g, and kinetic energy $\simeq 10^{26} - 10^{28}$ ergs.

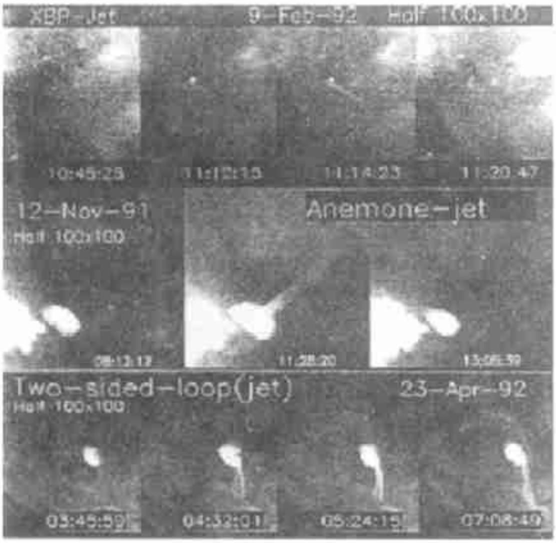

Fig.2 One XBP-jet (9–Feb–1992), one anemone-jet (12–Nov–1991) and one two-sided-loop (jet) (23–Apr–1992) [29]

2.4 Loop-loop interactions

According to the ratio of the typical scales of plasma pressure gradient in the z-direction (L_z) to that in the radial direction (L_r), there are three types of loop-loop interactions [31] (see Fig. 3): X-type corresponds to the case of $L_r/L_z \gg 1$, Y-type relates to $L_r/L_z \simeq 1$ and I-type is an opposite case of the X-type, i.e. $L_r/L_z \ll 1$. Yohkoh satellite observed some I-type [32,33] and X-type [34,35] interactions. Using Yohkoh SXT data, Shimizu et al.[36] found that among 144 X-ray transient brightening events, 69 ones correspond to multi-loop events, in which 30% belong to X-type and 57% are Y-type interactions. Other interaction events were also reported [38]. All these loop-loop interactions produce only small flares or X-ray brightenings.

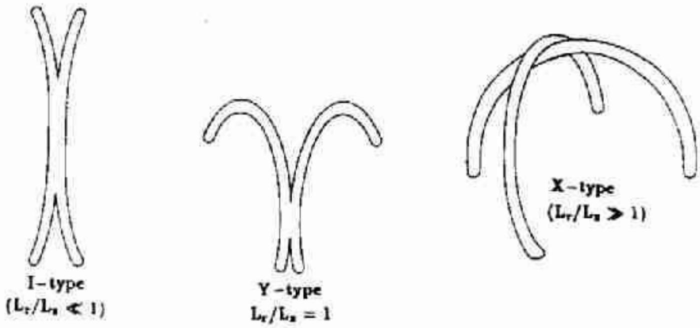

Fig.3 Three types of loop-loop interactions

In the optical waveband, Smartt et al.[38] analyzed the coronograph data in 1979–1989 at the National Solar Observatory of the United States and found more than 90 coronal loop-loop interaction events. Their total energy was estimated to be $\sim 6 \times 10^{28}$ ergs. Vrsnak et al.[39] reported also one example. In radio waveband, there is also some evidence for loop-loop interactions (e.g. [40,41]), but they are mainly indirect. Recent numerical simulation[42] indicated that low β plasma during a Y-type interaction shows a rapid pinch and enhancement of all physical quantities, while for an X-type interaction, the increase of the plasma β causes a high velocity jet. For a I-type collision, it shows neither jet nor very strong enhancement of physical quantities.

It should be mentioned that although flares often consist of multiple loops, it is not often possible to prove that they have physical interaction, because of the observational limitations even for the advanced Yohkoh satellite, as Hudson [43] indicated. Although some authors think that loop-loop interactions do exist, they still should be studied further.

2.5 Dynamics of flare atmosphere

Since the 1980s, it has been well known that the atmosphere of flares undergoes a tremendous dynamic process during the flare development. The most widely accepted scenario has been the chromospheric evaporation model (CEM)[44]. This model assumes that a sudden energy release due to the reconnection of magnetic field produces particle beams and/or conduction fronts, which go down along the pre-existing coronal loop and encounter the dense chromosphere, resulting in the heating of the chromospheric plasma. Then the hot material expands up along the legs of the loop, resulting in the blue asymmetry of the lines of highly-ionized atoms. At the same time, the high pressure drives the cool chromospheric plasma going down to the low atmosphere and forming the chromospheric condensation, which causes the observed red asymmetry in the chromospheric lines (Hα, CaII K etc.)[45]

Some recent space observations, such as that from Yohkoh (e.g. [46]), support the above described CEM scenario. However, there are some new discoveries, which give a challenge to the CEM. For example, Seely *et al.* [47] analysed the SXT images of over fifty flares and found that the 10 million degree emitting region of each flare was typically located at the loop top during the rise phase and lasted for a long time. For the 2 November 1992 limb flare, the loop top was bright for 24 hours. These results are not explained by the CEM. Cheng *et al.*[48] have analysed, using a moment method, CaXIX and FeXXV spectra for 64 flares observed by BCS/Yohkoh. They found that the mean mass motion velocity is around 100 km $\cdot$s^{-1} or less. It was also found that many flares showed an upflow of several tens of kilometers per second at several minutes before the onset of the hard X-ray emission. Fig. 4 shows the result for the 22 April 1993 flare. These facts imply that the preflare heating, which produces the observed pre-impulsive upward motions, is needed for the electron acceleration during the impulsive phase.

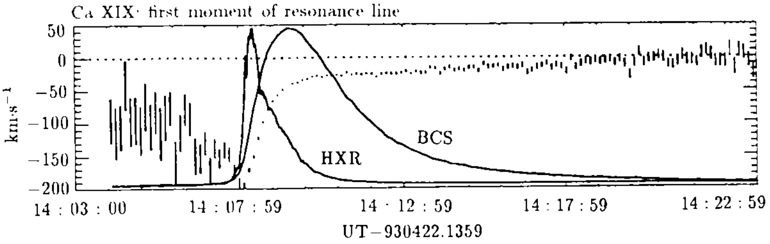

Fig.4 Mass motion velocity derived from CaXIX spectra for the 22 April 1993 flare. Negative values represents upward motion [48]

What is the response of the low atmosphere to the energy release in the corona during the flare? How can the response happen? These are also interesting problems. The most obvious evidence of the mass motion in the low atmosphere is the asymmetry of the line profiles which form in the chromosphere and the photosphere. In the 1980s, there was a great deal of work on the asymmetry of line profiles, mainly for Hα lines (see the review paper [45]). During the rise phase of flares, the downward velocity derived from the red asymmetry of Hα lines is typically around 40–100 km $\cdot$s^{-1} [49,50]. It is believed that the asymmetry comes from the effect of the chromospheric condensation, which goes downward. Recent high-resolution spectral observations show[51,52] that the maximum of the red asymmetry is coincident with the peak of hard X-ray emission. It is also found[51] that for two flares on 21 October 1989, the velocities derived from CaII K and D_3 lines are as large as Hα velocity. However, we analysed the CaII K lines for 12 flares and found[53,54] that the typical velocity derived from the asymmetries at the line wings is 10–30 km $\cdot$s^{-1}. Our non-LTE calculation indicated[53] that a downward motion of plasma above the temperature minimum region (TMR) plus a upward motion of the photosphere plasma toward the TMR can well explain the observed asymmetry at the K_1 positions of CaII K lines. Our analyses on the metallic lines have shown[55,56,57] that red asymmetries dominate in strong metallic lines, but blue asymmetries also exist in some weak lines and the line centers have no obvious shift. It should be mentioned that our high-resolution observation explored a new fact[57]. That is, the spectral line asymmetry has spatial fine structure of $1''$- $2''$, and for several points in the flare region, the Hα line profile alternatively changes between blue asymmetry and red asymmetry within a few seconds. Another point should be stressed: the predicted duration of the condensation given so far by the calculations[58] is much shorter than the observed one, though the simulations given by Ding and Fang[59,60] improved the situation to some extent. Thus, further studies, both in observation and theoretical work are required.

3 Comments and Remarks

As described above, some recent important progress in the study of solar flares has been achieved during the past No.22 solar cycle. However, high-resolution observations, especially from the Yohkoh satellite, have explored some new phenomena, which are previously unknown and contrary to the conventional concepts and models. For example:

(1) Most flares do not have cusp configurations, which are thought to be one of the manifestations of current sheet reconnections in flares, and a soft X-ray cusp often appears to be passive and to be present outside the time of major flare energy release.

(2) Reconnection inward flows are usually not detectable, except for the soft X-ray jets on smaller scales. Furthermore, there are many flares with no observable eruptive behavior.

(3) Loop-loop interactions, which are believed to be one of the necessary conditions for the reconnection happening, have not found strong support, especially for the major flares.

(4) It is not known that the chromospheric evaporation and the condensation are common

for most of flares. Even so, the properties of the evaporation and the condensation are still not clear.

(5) Thus, it is still not clear whether the reconnection signatures Yohkoh sees in some flares are the direct cause of the energy release in the flare, or they are driven by the flare energy release.

Thus, although recent progress in the study of solar flares has brought us much new knowledge and many exciting discoveries, they also raise a lot of questions and mysteries, the number of which is probably as large as that of the solved ones. Further high resolution observations as well as quantitative theoretical work are highly desirable.

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