INVITED REVIEWS

Recent progress of solar physics research in China

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Abstract Owing to the largely improved facilities and working conditions, solar physics research in China has recently shown marked development. This paper reports on the recent progress of solar physics research in Mainland China, mainly focusing on several hot issues, including instrumentations, magnetic field observations and research, solar flares, filaments and their eruptions, coronal mass ejections and related processes, as well as active regions and the corona, small-scale phenomena, solar activity and its predictions. A vision of the future is also described.

Key words: Sun: general — Sun: coronal mass ejections (CMEs) — solar physics: recent progress

1 INTRODUCTION

In ancient history, Chinese astronomy, including solar physics, made glorious achievements. The main purpose of ancient Chinese astronomy was to study the correlation between man and the universe. This made ancient Chinese astronomy a highly regarded science by the emperors. The Sun as the nearest star certainly attracted much attention. For instance, solar eclipses were already mentioned in oracle bone inscriptions from the Shang Dynasty (1600 BC – 1046 BC). The first well-recognized sunspot record was made in 28 BC, during the Han Dynasty, which was described as a “dark air like coin on the Sun.” From the Han to the Ming Dynasties, there were more than 100 sunspot records (Xu & Jiang 1986). Modern Chinese solar observations started in 1925 at Qingdao Observatory, which was a former German establishment taken over and renamed by the Chinese government. Regular solar sunspot drawings made by naked eye were recorded there.

Since the 1980s, solar physics research has quickly developed in China (see e.g. Fang et al. 2008). The main participating organizations include the National Astronomical Observatories of China (NAOC, Beijing), Purple Mountain Observatory (PMO), Yunnan Astronomical Observatory (YAO, NAOC), Nanjing University (NJU, established in 1952), Peking University (PKU, 1960), Beijing Normal University (BNU, 1960), the University of Science and Technology of China (USTC, 1978), and Shandong University at Weihai (2008). At present, about 50 scientists (professors and researchers), 16% of the total number of astronomers in China, are engaged in solar physics investigations. In addition, there are currently more than 80 graduate students in different solar research groups.

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In this paper we will give a brief description of the recent progress of solar physics research in Mainland China. After introducing the instruments in Section 2, a brief review on magnetic field observations and research, as well as solar flares, filament eruptions, active regions, coronal mass ejections, small-scale processes, solar activity and its predictions will be given in the successive Sections. The discussion and conclusion will be given in the last Section.

2 INSTRUMENTATIONS

In recent years the instruments for solar observations in China have been improved. At NAOC solar observations are concentrated at Huairou Solar Observing Station (HSOS). The key instruments at HSOS are as follows:

(1) A Solar Multi-Channel Telescope (SMCT) (Ai & Zhang 1992) which includes a 60 cm Solar Nine-Channel Telescope, a 35 cm solar magnetic field telescope, a 14 cm full-disk and partial Hα imaging telescope, and a 20 cm full-disk Hα telescope. The SMCT can simultaneously measure the solar magnetic field and velocity field with different spectral lines. Figure 1 gives the overview of SMCT and an example of its magnetogram. The SMCT has been working continuously and making routine magnetic field observations since 1984 (Lin & Wang 2009).

(2) A Broadband Solar Radio Spectrograph (BSRS) (Fu et al. 2000) which is composed of five spectrometers at different frequencies: 0.7–1.4 GHz (at YAO), 1.0–2.0 GHz, 2.6–3.8 GHz, 4.0–5.2 GHz (at PMO) and 5.2–7.6 GHz.

(3) A Solar Magnetism and Activity Telescope (SMAT) has been operated since 2005 (Zhang et al. 2007a,d; Wang et al. 2010a), which makes full solar disk vector magnetic field and Hα observations. It is suitable for monitoring solar activity.

Recently the Chinese Spectral Radio Heliograph (CSRH) was constructed at Zhengxiangbaiqi, Inner Mongolia (Yan et al. 2009b). The frequency coverage is ∼0.4 – 15 GHz (75 – 2 cm) with a resolution of 64 or 128 channels in 0.4 – 2 GHz, and 32 or 64 channels in 2 – 15 GHz. The

Fig. 1 Solar magnetograph telescope (left) and an example of a magnetogram obtained by the telescope (right).
spatial resolution is $1.3'' - 50''$, depending on frequency. The temporal resolution is $< 100$ ms at 0.4–15 GHz and the dynamic range is 30 db (snapshot). CSRH has an array with $40 \times 4.5$ m and $60 \times 2$ m parabolic antennas. The largest base line is 3 km and the field of view is $0.5^\circ - 7^\circ$.

The main facilities for solar observations at PMO include a multi-channel near-infrared spectrograph (Li et al. 1999), which is used to observe 2D solar spectra at Hα and He I 10830 A, and a 26 cm fine structure telescope with a FOV of $4' \times 6'$ for observing solar images at Hα and white light.

At YAO (NAOC) a series of telescopes are in operation: a full disk Hα monitor, a 26 cm fine structure telescope with FOV of $4' \times 6'$, an 11 m radio telescope working at 70 –700 MHz since 2008, a 10 m radio telescope working since 1999 at 625 –1500 MHz with high temporal resolution, and three antennae with diameters of about 3–4 meters at 1.42, 2.00, 2.84, and 4.00 MHz, which started to work at the end of the 1980s.
Recently a new 1 m solar vacuum telescope has been installed near Fuxian lake, which is 60 km away from Kunming (see Fig. 2). At present it is the place with the best seeing in China (Liu & Beckers 2001). A detailed description can be found in Liu & Xu (2011).

In Nanjing University a solar tower was put in operation in 1980 (Fang & Huang 1983). It has a multi-channel spectrograph which can be used to obtain 2D spectra in Hα, 8542 Å and 10830 Å wavebands simultaneously (Huang et al. 1995). Recently a new telescope called ONSET (Optical and NIR Solar Eruption Tracer) has been established near Fuxian lake at the observational base of YAO. ONSET can provide three images of the full or partial disk (10 arcmin) of the Sun at wavelengths of Hα 6563 Å (FWHM 0.25 Å± 1.5 Å), 10830 Å (FWHM 0.5 Å± 1.5 Å), and 3600 Å or 4250 Å. The cadence of the routine observations will be one minute. Figure 3 shows an overview of ONSET and an example of an Hα image recorded on 2011 April 18.

3 MAGNETIC FIELD OBSERVATIONS AND RESEARCH

Magnetic fields are the controlling factor that drives active phenomena such as flares and coronal mass ejections (CMEs). Understanding the production and evolution of magnetic fields has been an important issue in current solar physics study. Chinese scientists have contributed much to this field.

Wang & Zhang (2010) found that the usual hemispheric helicity sign rule is present everywhere in the global magnetic field, extending to 60° in solar latitudes, independent of the instruments and parameters used, and is evident at both solar maximum and minimum phases. Hao & Zhang (2011) used vector magnetograms obtained with the Spectro-polarimeter (SP) onboard Hinode and found that active regions in the ascending phase of solar cycle 24 follow the hemispheric helicity sign rule, whereas active regions in the descending phase of solar cycle 23 do not. Gao et al. (2009) made a comparison between photospheric current helicity and subsurface kinetic helicity in active regions. Their result does not support the idea that the photospheric current helicity has a cause and effect relation with the kinetic helicity at 0–12 Mm beneath the solar surface. Yang et al. (2009a) found that the magnetic helicity was transferred from the late emerging AR 9192 to a previous AR 9188 via an unbalanced magnetic torque along a loop. Such kinds of helicity transfer might be a common mechanism of redistribution of magnetic helicity in the solar atmosphere, which has not yet been widely observed.

Some studies focus on the properties of magnetic intra-networks. Wang et al. (1995) pointed out that even though these fields are relatively weak, they still contribute more than 20% of the total magnetic flux on the Sun. In recent years these weak magnetic fields and small-scale magnetic structures have attracted increasing attention. Zhou et al. (2010) determined the average lifetime of intra-network elements to be 2.9±2.0 min. Based on the observations with high spatial resolution and sensitivity from SP/SOT, Jin et al. (2009) statistically studied the vector magnetic field of the solar granulation, and reconstructed an average granular cell model. Zhao et al. (2009a) found that the magnetic fields of the quiet region are obviously non-potential in nature, and the filigrees and network bright points are magnetically characterized by strong longitudinal fields, large electric helicity, and high free energy density. With data from the Michelson Doppler Imager (MDI) onboard the Solar and Heliospheric Observatory (SOHO) in solar cycle 23, Jin et al. (2011) found three categories of small-scale magnetic elements, whose number and total flux variations show no correlation, anti-correlation, and correlation with sunspots, respectively. Furthermore, in the entire cycle, the quiet regions contributed (0.94–1.44)×10^{23} Mx flux to the Sun from the solar minimum to maximum, and the monthly average magnetic flux of the quiet regions is 1.12 times that of the active regions.

Jin & Wang (2011) analyzed the magnetic field in the solar polar regions. They found that the kG field occupies 6.7% of the region, and the ratio of the magnetic flux in the minority polarity to that in the dominant polarity is approximately 0.5, implying that only 1/3 of the magnetic flux in the polar region opens to interplanetary space.
Recently, the magnetic fields in the coronal holes have been studied in detail. Zhang et al. (2006a) found that the evolution of magnetic flux in a quiet region is much faster than that in a coronal hole, and in the coronal hole, stronger fields are occupied by one predominant polarity, but the majority of weaker fields are occupied by the opposite polarity. Using Big Bear Solar Observatory (BBSO) deep magnetograms and SOHO/EIT images observed from 2005 October 10 to 14, Zhang et al. (2007c) explored the magnetic flux evolution and temperature variation in a coronal hole region and in a neighboring quiet one. Their results demonstrated that in the coronal hole less imbalance of the magnetic flux in opposite polarities leads to stronger EUV brightness and higher coronal temperatures. Yang et al. (2009b) noticed that dipoles play an important role in coronal hole evolution and observed submergence of original magnetic loops in the coronal hole. Yang et al. (2009c) found that, in an equatorial coronal hole, there is a close positive linear correlation between the network magnetic flux densities and the brightness of both the $G$ band and Ca II H. Using Hinode data, Yang et al. (2011a) investigated, for the first time, vector magnetic fields, current densities, and current helicities in two coronal holes, and compared them with two normal quiet regions. Their results indicate that the magnetic fields, especially the strong fields, both in the coronal holes and in the quiet regions are non-potential in nature. With the observations from the Solar Dynamic Observatory (SDO), Yang et al. (2011b) found signatures of magnetic reconnection at coronal hole boundaries and noted that magnetic reconnection at coronal hole boundaries maintains the rigid rotation of coronal holes.

Based on the spectral scan data of NOAA AR 10325, 10484 and 10377 obtained with the SMCT at HSOS, Su et al. (2006) and Gao et al. (2008) found that the azimuthal rotations caused by Faraday rotation are closely correlated with the longitudinal field and inclination. The result indicates that it is advisable to carry out the statistical correction for Faraday rotations in the vector magnetograms taken by a filter-type vector magnetograph.

The extrapolation is still a main method to study the coronal magnetic field. Some Chinese scientists provided several methods to obtain the nonlinear force-free (NLFF) field based on the observed data. Yan & Sakurai (2000) and Yan & Li (2006) developed a direct boundary integral method (DBIE), while Song et al. (2006, 2007) proposed an approximate vertical integration (AVI) method. Recently Liu et al. (2011) conducted a study to compare the results from DBIE, AVI, an optimization method (Wiegelmann 2008) and two semi-analytical solutions of force-free fields. It is found that differences in the computed field strengths exist in the layers, However, they tend to disappear as the height increases. Some difference in azimuth angles between each NLFF field model exists, but is not so significant.

Another way to investigate the magnetic field in the corona is by using radio observations. Zhou & Li (2007) computed the gyrosynchrotron spectra in a nonuniform magnetic field case, taking into account the self- and gyro-resonance absorption. They found that there are good positive linear correlations between the peak radio frequency and the photosphere magnetic field strength $B_0$, and that the evolutionary tendencies of $B_0$ estimated from the above expression are comparable with the observational results of SOHO/MDI. They also gave a comparison of the diagnostic results of coronal magnetic field strength in both uniform and nonuniform source models.

4 SOLAR FLARE

Since the 1980s, the study of solar flares has attracted the attention of many Chinese solar physicists. Recently this field of study has been extended widely. It includes spectroscopy and non-LTE modeling, magnetic flux rope and trans-equatorial loop configurations, magnetic field change and evolution, the contraction phenomenon of flare loops, the Neupert effect, microwave, X-ray and $\gamma$ emissions, as well as energetic particle events, etc. Here we briefly describe some of the recent results.

The Solar Tower Telescope of Nanjing University observed hundreds of solar flares in the last solar maximum. The multi-wavelength spectral data provide a good opportunity to study the heating
and emission mechanisms of solar flares. Liu et al. (2001) found that in a white light flare (WLF) of 2001 March 10, the near infrared (Brackett) continuum was increased relative to the quiescent level. Moreover, the observation also showed evidence of continuum dimming at the beginning of the flare. By making non-LTE model calculations, Ding et al. (2003) interpreted the origin of the infrared continuum increase in terms of an electron-beam-heated flare model and the back-warming in the temperature minimum region and upper photosphere. Chen & Ding (2006) found a footpoint motion of the continuum emission which is spatially similar to the motion of the hard X-ray source, implying a significant role of electron beams in powering the WLFs. Using radiative hydrodynamic simulation, Cheng et al. (2010a) quantitatively investigated the continuum emission in the atmosphere resulting from electron beam heating. The results show that most WLFs can be explained in terms of electron beam heating plus the back-warming effect.

Magnetic flux rope is found to play an important role in the onset of solar eruptions (Guo et al. 2010d; Cheng et al. 2010b). Figure 4 shows the magnetic rope, which is obtained through extrapolation of the magnetic field in the photosphere (Guo et al. 2010). Cheng et al. (2011) reported observational evidence of a flux rope using the high resolution data of SDO/AIA.

For the major solar activity in 2004 November, Wang et al. (2007) indicated that solar transequatorial activities are very common and manifest through (1) the formation and eruption of trans-equatorial loops and trans-equatorial filaments, and (2) the trans-equatorial flare. These authors noticed the coupling of flares in active regions and the trans-equatorial solar activity, and revealed that the coupled events had a lifetime of more than 12 hours with prolonged acceleration of CMEs (see Fig. 5).

Analyzing the X7.1 solar flare on 2005 January 20, Wang et al. (2009c) found definitive evidence of strengthening of the horizontal fields in an extended area centralized at the magnetic neutral line between major sunspots of opposite polarities. Zhao et al. (2009b) found that a flare-induced signal can be seen in transverse magnetograms but with smaller magnitude. Su et al. (2011) analyzed photospheric vector magnetograms covering five flares to study the two-dimensional spatial distributions of the changing Lorentz force (LF). They found that around the major flaring polarity inversion line, the net change of the LF is directed downward in an area of $10^{19}$ cm$^2$ for X-class flares. For all events, the white-light observations show that sunspots darken in this location after flares, and magnetic fields become more inclined. Jing et al. (2009) studied the temporal variation of free magnetic energy around the time of four X-class flares. They found a significant drop of free magnetic energy starting 15 minutes before the peak time of the associated nonthermal flare emission. It implies that the magnetic relaxation is probably already ongoing in the corona well before the flare reconnection. Zhang et al. (2009b) performed a statistical study of the relationship between the transport rate of magnetic helicity and solar flares. They found that some flares (type I flare) are associated with sharp variations of the transport rate (dH/dt) of magnetic helicity while others are not (type II flare). Their results indicate that whether the flare is associated with sharp variations of dH/dt depends on the properties of the flare and of its host active region.

Wang & Zhang (2007) examined eruptive and confined flares. They found that about 90% of X-class flares are eruptive, but the remaining 10% are confined. By investigating four X-class events from each of the two types, it was found that confined events occur closer to the center of active regions, but the eruptive events tend to occur close to the edge, and a stronger overlying arcade field may prevent energy releases in the low corona from becoming eruptive, resulting in flares without CMEs.

Magnetic null points in the 3D coronal structure favor the formation of a current sheet, a signature of magnetic reconnection, which leads to eruptions. The magnetic null points in the corona above active region AR 10486 have been identified (Li et al. 2006; Schmieder et al. 2007). However, their results indicated that the existence of the two null points has no crucial role in triggering the main flare of 2003 October 26 and the presence of magnetic null points does not always lead to the occurrence of flares.
**Fig. 4** Selected magnetic field lines of the active region (red) and the flux rope (mixed colors) on 2005 May 27. (a) Top view on the magnetic flux rope. Different colors are used to outline the twist of the field lines. Red, dark blue, and green field lines are calculated by integrating from three selected points slightly above the inversion line into both directions. Orange field lines are selected close to the magnetic flux rope. (b, c) Side views of the magnetic flux rope. The vertical scale is enlarged by a factor of three. From Guo et al. (2010d).

**Fig. 5** Time sequence of EIT images and X-ray light curves, showing the coupling of flares in AR 10696 and trans-equatorial loop (TEL) activities. Light curves of the TEL are shown by the green dotted and dashed lines. GOES soft X-ray flux changes in the energy bands of 0.05–4.0 Å are shown by the light blue line and 1.0–8.0 Å are displayed by the light red line (Wang et al. 2007).
The study of the magnetic field configuration and evolution of the flare-productive AR 10808 suggested that continuous emergence of a sheared and twisted magnetic flux tube easily leads to large solar flares (Li et al. 2007d). Such an emergence is frequently indicated by the tongue-shape of the two main polarities of an active region.

Large broadenings of the Hα line are observed a few minutes after the flare onset within small regions of $3'' - 5''$ with/without non-thermal processes (Li et al. 2007e). Such large broadenings are observed in both the footpoints and the flare loop-top regions, and possibly result from strong turbulence and/or macroscopic motions. Therefore, the so-called “non-thermal wing” of the Hα line profile is not a sufficient condition to distinguish whether non-thermal electrons are accelerated or not in a flare.

In recent years, a kind of contraction phenomenon of flare loops during the rising phase of solar flares has been explored in Hα (Ji et al. 2004, 2006, 2008; Zhou et al. 2007) and in radio and EUV wavelengths (Li & Gan 2005b, 2006). It is found that during the early impulsive phase of solar flares, HXR looptop (LP) sources or radio/EUV flaring loops have a descending or shrinking motion and, at the same time, Hα ribbons or HXR footpoints (FPs) are converging. Only after the impulsive phase does there begin to appear an upward motion for the looptop sources and flaring loops and a corresponding outward separation motion for the flare ribbons or FPs. In most times, the converging motion and the separation motion of FPs are a kind of unshearing motion, traveling at tens of kilometers per second. All results indicate that the magnetic reconnection occurs in a sheared magnetic field during the early impulsive phase and energy released during this period dominates all flare energetics. During the impulsive phase, the energy release signature is much more apparent from magnetic fields other than plasma thermodynamics (Ji et al. 2007). Shen et al. (2008) found...
that during the contraction period, the temperature structures of the looptop sources in the 8–10, 10–13, and 13–16 keV energy bands are almost mixed with one another as seen in Figure 6. The abnormal temperature distribution obviously suggests a complex magnetic reconnection process in the contraction period, which can be linked with step-wise magnetic changes reported in many flares (e.g., Wang et al. 2009c, 2011b).

The Neupert effect, which is probably caused by nonthermal electrons, has been extensively studied by Ning (2008, 2009), who reported a high correlation between the hard X-ray flux and the time derivative of the thermal energy deduced from X-ray spectral fits and an anti-correlation between the hard X-ray spectral index and the time rate of change of the UV flare area observed by the Transition Region and Coronal Explorer (TRACE). Li et al. (2009e) studied a kind of flare observed by the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) that presents two successive peaks in 12–25 keV light curves. They showed some evidence to support the expected causal relationship between these two peaks within the framework of the chromospheric evaporation. They proposed that for some events, a modification of the traditional Neupert effect could be necessary by inclusion of a time delay, which might be partly related to the filling of the loop by evaporated material.

Huang & Nakajima (2009a,b) and Huang et al. (2010) statistically analyzed microwave flare loops of 24 flares and obtained the temporal evolutions of looptop and footpoint sources, regarding the brightness temperature, polarity degree, spectral index, strength of magnetic field, and column density of electrons. They found that: (1) all these parameters are correlated between LP and FPs or between two FPs; (2) FPs are usually softer than LP sources, but the spectral evolution behaviors of FPs and LP sources are similar; (3) the computed magnetic fields are stronger at FPs than at LP sources.

Li & Gan (2005a) showed the TRACE 195 Å images (post flare) together with the RHESSI images (impulsive phase) at different energy channels for the X4.8 flare of 2002 July 23, in which not only the morphology of the flare but also the rich properties of high energy sources can be clearly seen. In particular, the hard X-ray image between 28 and 38 keV shows both the footpoint and coronal sources (see Fig. 7).
An M2.6 flare observed with RHESSI on 2005 August 22 was studied by Li & Gan (2008). The light curves of the hard X-rays, the derived number fluxes, as well as the energy fluxes of energetic electrons all presented a damped quasi-periodic oscillation. The modulation depth of the hard X-rays increased with the energies. During the oscillations, however, the plasma temperature had no apparent change. Such an oscillation with a high modulation depth for a period of about four minutes still cannot be explained with the existing mechanisms.

The observed HXR spectrum cannot often be fitted by a single power law, but rather requires a downward break in the photon spectrum. Su et al. (2009b) found that for HXR spectra from a target with nonuniform ionization, the difference between the power-law indexes above and below the break has an upper limit between \( \sim 0.2 \) and 0.7. However, Li & Gan (2011) pointed out that sometimes the observed HXR spectrum presents an integrated broken-up form, which is produced either by the summation of individual sources or by the temporal variation of a single source, not by the acceleration itself.

Based on RHESSI observations, Gan (2004) studied three major \( \gamma \)-ray line flares, and explained both the time histories of the 0.511 MeV line and the 2.223 MeV line for the X4.8 flare of 2002 July 23 by adopting a time-varying power-law spectrum of accelerated ions. For the X17.2 flare of 2003 October 28 and the X8.3 flare of 2003 November 2, Gan (2005) fitted the time integrated spectra up to 7 MeV with a model with multiple components. He found that the annihilation region might be at the lower atmosphere for the November 2 event. It is also shown that the abundance of Ne/O tends to be 0.15 rather than 0.25, and that energetic \( \alpha/p \) tends to be within 0.01–0.1 but not bigger than 0.1.

Previous statistical analyses of a large number of SOHO/MDI full disk longitudinal magnetograms provided a result that demonstrated how responses of solar flares to photospheric magnetic properties can be fitted with sigmoid functions. Wang et al. (2009b) proposed a logistic model and indicated that these fitted sigmoid functions might be related to the free energy storage process in solar active regions. Although this proposed model is rather simple, the free energy level of active regions can be estimated and the probability of a solar flare with importance over a threshold can be forecasted within a given time window.

Using multi-wavelength data of Hinode, Yan et al. (2009a) studied the rapid rotation of a sunspot in active region NOAA 10930. They found extraordinary counterclockwise rotation of the sunspot with positive polarity before an X3.4 flare, and that magnetic force lines are highly sheared along the neutral line. A detailed analysis provided evidence that sunspot rotation leads to magnetic field lines twisting in the photosphere. The twist is then transported into the corona and triggers flares. Yan et al. (2007) analyzed the same active region, NOAA 10930, and found that the radio fine structures during the impulsive phase of the flare may be closely associated with coronal structures during the magnetic-reconnection process, as revealed by Hinode soft X-ray images. These microwave fine structure observations may provide very useful diagnostics at the primary energy release sites when they occur in the impulsive flare phase.

In large gradual solar energetic particle (SEP) events, especially the ground-level enhancement (GLE) events, where and how energetic particles are accelerated is still a problem. Li et al. (2007b) studied the evolution of the X5.7 two-ribbon flare and the associated SEP event on 2002 July 14. They found that a reconnection electric field makes a crucial contribution to the acceleration of relativistic particles and the impulsive component of the large gradual SEP event, while CME-driven shocks play a dominant role in the gradual component. An X17.2 solar flare occurred on 2003 October 28, accompanied by multi-wavelength emissions and a high flux of relativistic particles observed at 1 AU. Li et al. (2007a) presented the analytic results of the TRACE, SOHO, RHESSI, ACE, GOES, hard X-ray, radio, and neutron monitor data. It is found that the inferred magnetic reconnection electric field correlates well with the hard X-ray, gamma-ray, and neutron emission at the Sun. Thus the flare’s magnetic reconnection probably makes a crucial contribution to the prompt relativistic particles, which could be detected at 1 AU. Li et al. (2010a) made a statistical survey of 26 major electron events during the period 2002 February through the end of solar cycle 23. It is found
that 10 out of the 11 well-connected open field-line events are prompt events whose solar onset times coincide with the maxima of flare emission and 13 out of the 14 closed field-line events are delayed events. These correlations clearly establish a significant link between the coronal magnetic field-line topology and the escape of charged particles from the flaring active regions into interplanetary space during the major solar energetic particle events.

5 FILAMENTS AND THEIR ERUPTIONS

By using the SMCT installed at HSOS and the SOHO/MDI data, an S-shaped filament that underwent an eruption in a sigmoidal active region (AR 8027) was analyzed. The observations suggest that the eruption resulted from the interaction between the emerging bipole and the overlying loops (Jiang et al. 2007d). Guo et al. (2010a) presented an observation of a filament eruption caused by recurrent chromospheric plasma injections (surges/jets) on 2006 July 6. The filament eruption was associated with an M2.5 two-ribbon flare and a CME. Their study confirms that the surge activities can efficiently supply the necessary material for some filament formation, and that the continuous mass with momentum loaded by the surge flowing to the filament channel could make the filament unstable and cause it to erupt. Li et al. (2010d) reconstructed the three-dimensional shape and evolution of two eruptive filaments observed on 2009 September 26. For the first time, they investigated the true velocities and accelerations along the axis of the large filament. Li et al. (2011d) also reconstructed the three-dimensional geometry of a polar crown filament using observations from three different viewpoints (STEREO A, B and SDO), and found that all the activities were coupled together, suggesting a global character of the magnetic eruption.

Using Hα and white-light, EUV imaging, and spectroscopic data, Chen et al. (2008) reported an interesting event, in which a siphon flow was moving from the proximity of the prominence, and was followed by repetitive Hα surges and continual prominence oscillations. The oscillation lasted four hours before the prominence erupted as a blob-like CME. They proposed a precursor for CMEs, namely, long-time prominence oscillations. Ning et al. (2009) reported a drifting, oscillating, and hybrid nature for filament threads using Hα off-band data observed by Hinode.

Ji et al. (2003) reported an interesting “failed filament eruption,” as the filament material, seen in absorption by TRACE, first accelerated then decelerated as it approached its peak height of $8 \times 10^4$ km while the filament threads drained back to the Sun. The observation provides evidence that at least two conditions are required for a successful eruption: a reconnection very low in the corona (possibly above the filament) and open or opening fields above that point. The stereoscopic observations of six sequential eruptions of a filament in the active region NOAA11045 on 2010 February 8 indicated that the last one of the six eruptions is a coronal mass ejection, but the others are not. The results suggest that, besides the confinement of the coronal magnetic field, the energy released in the low corona should be another crucial element affecting a failed or successful filament eruption (Shen et al. 2011b). Liu et al. (2009) also reported the observation of two failed filament eruptions, which could be ascribed to the confinement of the coronal magnetic field on the erupting flux rope (or filament).

An automated system, called SLIPCAT, was developed by Wang et al. (2010b) to catch and track solar limb prominences based on observations from the EUV 304 Å passband. A preliminary statistical study with the STEREO/SECCHI/EUVI 304 Å data from 2007 April to 2009 October indicated that most prominences appear below the latitude of 60° and at the height of about 26 Mm above the solar surface, and the expansion of a prominence is probably one major cause of its fading during the rising or erupting process.

The mechanism of the filament formation is still an important issue. Xia et al. (2011) used grid-adaptive numerical simulations of the radiative hydrodynamic equations to investigate the filament formation process in a pre-shaped loop with both steady and finite-time chromospheric heating. They demonstrated for the first time that the onset of thermal instability satisfies the linear instability
criterion. The onset time of the condensation is roughly 2 hr or more after the localized heating at the footpoint is effective, and the growth rate of the thread length varies from 800 km hr\(^{-1}\) to 4000 km hr\(^{-1}\), depending on the amplitude and the decay length scale characterizing this localized chromospheric heating.

6 CORONAL MASS EJECTIONS

Coronal mass ejections (CMEs) are the largest-scale eruptive phenomenon in the solar system, expanding from an active region-sized non-potential magnetic structure to a much larger size. The bulk of plasma with a mass of \(10^{11} - 10^{13}\) kg is hauled up out to interplanetary space with a typical velocity of several hundred to 2000 km s\(^{-1}\). Some CMEs can impact the Earth, resulting in hazardous space weather conditions. They involve many other much smaller-sized solar eruptive phenomena, such as filament/prominence eruptions, solar flares, plasma heating and radiation, particle acceleration, EIT waves, EUV dimmings, Moreton waves, solar radio bursts, and so on. Chen (2011) compiled a comprehensive review of the CME pre-eruption structure, their triggering mechanisms and the precursors indicating the initiation process, their acceleration and propagation. Particular attention is paid to clarify some hot debates, e.g. whether magnetic reconnection is necessary for the eruption, whether there are two types of CMEs, how the CME frontal loop is formed, and whether halo CMEs are special, etc.

6.1 Characteristics of CMEs

6.1.1 Magnetic structures of the source regions

Zhou et al. (2006) presented the first classification of the large-scale magnetic structures associated with Earth-directed CMEs. The identified large-scale structures can be grouped into four different categories: extended bipolar regions (EBRs), transequatorial magnetic loops, transequatorial filaments and their associated magnetic structures, and long filaments along the boundaries of EBRs. Wang et al. (2006, 2007) reported the trans-equatorial filament eruption and its link to the flare/CME in the Bastille Day event. Zhou et al. (2007) found the source regions of the CMEs in 2003 October-November to be associated with a large-scale filament channel that went through six related active regions, four of which bear obvious quasi-simultaneous emergence of magnetic flux. Zhou et al. (2011) identified a large-scale transverse current sheet in a pre-flare state, which plays a key role in the CME initiation, and can extend from the corona to interplanetary space.

Li et al. (2009a) analyzed the X3.4 solar flare and a fast halo CME occurred on 2006 December 13, accompanied by a high flux of energetic particles recorded both in near-Earth space and at ground level. It is found that the initial particle release time coincides with the flare emission and that the spectrum becomes softer and the anisotropy becomes weaker during particle injection, indicating that the acceleration source changes from a confined coronal site to a widespread interplanetary CME-driven shock.

6.1.2 Halo CMEs and the missing rate

By manually checking the LASCO and EIT movies of all the 1078 LASCO CMEs from 1997 to 1998, Wang et al. (2011c) discuss the missing rate of CMEs, the composition of CME mass and the cause of halo CMEs, which are important for us to correctly understand CMEs viewed in coronagraphs. Their statistical study suggests that (1) about 32% of front-side CMEs cannot be recognized by SOHO instruments, which indicates a large missing alert of interplanetary CMEs or geomagnetic storms, (2) density enhancement caused by CMEs in the corona is roughly positively correlated to the CME speed, that implies a significant contribution from ambient solar wind to the density enhancement, and (3) both projection effect and violent eruption are the major causes of halo CMEs,
and especially for limb halo CMEs the latter is the primary one. Zhang et al. (2010) analyzed 31 limb CMEs that clearly display loop-shaped frontal loops, and the results show a strong tendency that slower CMEs are weaker in white-light intensity. They made a Monte Carlo simulation of 20,000 artificial limb CMEs that have an average velocity of $\sim 523 \text{ km s}^{-1}$ and found that the white-light intensity of many slow CMEs becomes remarkably reduced when they turn from being viewed as a limb event to being viewed as a halo event. When the intensity is below the background solar wind fluctuation, it is assumed that they would be missed by coronagraphs. The average velocity of “detectable” halo CMEs is $\sim 922 \text{ km s}^{-1}$, which is very close to the observed value. The results suggest that the higher average velocity of halo CMEs is due to a majority of slow events and some narrow fast events carrying less material being so faint that they are blended with the solar wind fluctuations, and therefore are not observed. Yan et al. (2011) carried out a statistical study of 120 events observed in the period from 1998 to 2007 to better understand the relation of the active-region eruptive filament to the associated flares and CMEs. They found that 115 out of 120 eruptive filaments were associated with flares, while 56 out of 105 eruptive filaments were found to be associated with CMEs, except for 15 events without the corresponding LASCO data. They noticed the limitation of observations by the coronagraph that may lead to many smaller Earth-directed or out of the plane-of-sky CMEs not being detected. The CME association rate of the active-region eruptive filament clearly increases with X-ray flare class from about 32% for C-class flares to 100% for X-class flares. The average speed of CMEs associated with filament eruptions increases from 560 $\text{ km s}^{-1}$ for C-class flares to 1500 $\text{ km s}^{-1}$ for X-class flares.

6.1.3 Velocity of CMEs and shocks

Chen & Zong (2009) presented a statistical analysis of the relationship between CME velocities and X-ray fluxes of the associated flares. It is found that the correlation between the CME velocities and the peak X-ray fluxes is stronger than that between the CME velocities and the time-integrated X-ray fluxes of the associated flares. Guo et al. (2007) carried out a systemic study and found that for CMEs initiating in active regions, there is a relatively good correlation between the speed of CMEs and the value of so-called effective distance. In order to estimate the overall influence of the projection effects on the kinematic properties of the CMEs, Wu & Chen (2011) performed a forward modeling of real distributions of CME properties, such as the velocity, the angular width, and the latitude. They found that (1) the average real velocity of all non-full-halo CMEs is about 514 $\text{ km s}^{-1}$, and the average real angular width is about $33^\circ$, in contrast to the corresponding apparent values of 418 $\text{ km s}^{-1}$ and 42.7$^\circ$ in observations; (2) For the CMEs with the angular width in the range of $20^\circ$ – $120^\circ$, the average real velocity is 510 $\text{ km s}^{-1}$ and the average real angular width is 43.4$^\circ$, in contrast to the corresponding apparent values of 392 $\text{ km s}^{-1}$ and 52$^\circ$ in observations. Wang & Zhang (2008) investigated 57 of the fastest ($> 1500 \text{ km s}^{-1}$) front-side coronal mass ejections (CMEs) from 1996 June to 2007 January, and showed that the larger, stronger and more complex active regions have a greater possibility of producing fast CMEs. Wang et al. (2011a) made a statistical study and indicated that 68 out of 71 CME events are associated with the radio type III bursts or fine structures in the centimeter-metric frequency range during the initiation or early stages of the CMEs. This indicates that most CMEs contain the emissions of radio type III bursts/FSs near the time of the CME’s onset, in spite of their fast or slow speeds.

A generic self-similar flux rope model is proposed to probe the internal state of CMEs in order to understand the thermodynamic process and expansion of CMEs in interplanetary space (Wang et al. 2009e). Using this model, three physical parameters and their variations with heliocentric distance can be inferred for the first time based on coronagraph observations of CMEs’ propagation and expansion.

The strength of shocks plays a key role in shock-related phenomena, such as radio bursts and solar energetic particle (SEP) generation. Shen et al. (2007) improved the method of calculating
Alfvén speed and shock strength near the Sun. Their results suggest that slow CMEs drove a strong shock, while fast CMEs drove a relatively weak shock. This is consistent with the radio and SEP observations.

6.1.4 Current sheets

Lin et al. (2007) carefully investigated detailed patterns of the reconnection inflow near the current sheet, and realized that a boundary exists that separates the outside of the sheet that is characterized by the reconnection inflow from the inside of the sheet that is dominated by the reconnection outflow. Separation of the boundary on either side of the current sheet determines the thickness of the sheet. Direct measurements yielded that the apparent thickness of the reconnecting current sheet in the solar flare/CME process could be as large as a few times $10^4$ km. Lin et al. (2009) further studied the scale of the current sheets observed in three different events, and found that the apparent thickness of the sheets in these events ranged from $10^4$ to $10^5$ km, and that the impact of the projection effects and possible complex structure of the sheet itself on measuring the thickness is limited. Numerical MHD simulations have been conducted for reconnection in the two-ribbon flare. The results show apparent turbulent features inside the current sheet, and the sheet thickness eventually remains roughly a finite constant (e.g., see Shen & Lin 2009; Shen et al. 2011a). Hence huge values of the thickness of the reconnecting current sheet observed in the CME/flare process are probably not very unreasonable.

6.1.5 EIT wave and Moreton wave

The origin of the Moreton wave observed in the chromosphere and the EIT wave observed in the corona during the eruption remains an active research subject (see e.g. Wills-Davey & Attrill 2009; Chen 2011). Coronal “EIT waves” appear as EUV bright fronts propagating across a significant part of the solar disk (Thompson et al. 1998). This intriguing phenomenon provoked continuing debates on their nature and their relation with CMEs.

In order to determine whether EIT waves are generated by CMEs or pressure pulses in solar flares, Chen (2006) studied 14 non-CME-associated energetic flares, which should possess strong pressure pulses in their loops. It was found that none of these flares were associated with EIT waves. Particular attention was paid to AR 0720, which hosted both CME-associated and non-CME types of flares. The SOHO/EIT images convincingly indicate that EIT waves and expanding dimmings appear only when CMEs are present. Therefore, it is unlikely that pressure pulses from flares generate EIT waves.

Several models, such as the fast-mode wave model, the successive field-line stretching model, the successive reconnection model, and the slow-mode (soliton) wave model, have been proposed so far (see Chen 2011). Chen et al. (2002, 2005) proposed that EIT waves are apparent motions of brightenings that are generated by compression as the magnetic field lines overlying the erupting flux rope are successively pushed to stretch upward.

Figure 8 depicts the evolutions of the density (color), magnetic field (lines), and velocity (arrows) in the MHD simulation (top row), the evolution of the density distribution near the solar surface showing a coronal Moreton wave ahead of the EIT wave (bottom-left panel), and a sketch of the field-line stretching model for EIT waves (bottom-right panel). This model can explain the observed velocity, the stop of EIT waves at the magnetic separatrices, and the co-spatiality of EIT wavefronts with the CME frontal loop (Chen 2009; Dai et al. 2010). It predicts that the CME-driven shock wave is the counterpart of the Hα Moreton wave, which precedes the associated EIT waves. Chen & Wu (2011) confirmed the coexistence of a faster wave and an EIT wave with recent SDO observations. Chen et al. (2010) studied the dynamics at the EIT wavefront and found that the line widths increase at the dimming edge, a feature that can be explained by the EIT wave model of the
Yang & Chen (2010) investigated the relation between the EIT wave velocity and the local magnetic field in the corona. It was found that in most of the EIT wavefronts, the EIT wave propagates more slowly in the regions of stronger magnetic field. Such a result poses a big challenge to the fast-mode wave model, which would predict a strong positive correlation between the two parameters, but can be explained by the fieldline stretching model.

Wang et al. (2009a) numerically investigated the evolutionary features of the magnetic configuration that includes a current-carrying flux rope, after the loss of equilibrium takes place in a catastrophic process. Their results indicated that rapid motions of the flux rope following the catastrophe invoke the velocity vortices behind the rope, and may invoke as well slow and fast mode shocks in front of the rope. The velocity vortices on each side of the flux rope propagate roughly horizontally away from the area where they are produced, and both shocks expand toward the flank of the flux rope. They noticed that the fast mode shock may eventually reach the bottom boundary and it produces two echoes moving back into the corona, but the slow shock and the vortices totally decay somewhere in the lower corona. The interaction of the fast shock with the boundary leads to a disturbance that may account for the Moreton wave observed in Hα, and the disturbance in the corona caused by the slow shock and the velocity vortices may account for the EIT wave. However, Zhang et al. (2011) found that the location swept by Moreton waves had a relatively weak magnetic field as compared to the magnetic fields at their sidewalls. The ratio of the magnetic flux density

**Fig. 8** Top row: Evolutions of the density (color), magnetic field (lines), and velocity (arrows) in the MHD simulation of Chen et al. (2002); Bottom-left panel: Evolution of the density distribution near the solar surface showing a coronal Moreton wave ahead of the EIT wave; Bottom-right panel: A sketch of the field-line stretching model for EIT waves proposed in Chen et al. (2002) and Chen et al. (2005).
between the sidewalls and the path falls in the range of 1.4 to 3.7 at a height of 0.01 solar radii. How we can understand this observation is worthy of study.

6.1.6 Interaction with other processes

Interactions among various magnetic structures in the corona are also an important issue related to the eruption and the possible causes of severe space weather conditions. Jiang et al. (2009) presented the first evidence for occurrences of magnetic interactions between a jet, a filament and coronal loops during a complex event, in which two flares sequentially occurred at different positions of the same active region and were closely associated with two successive CMEs, respectively. Jiang et al. (2007b), for the first time, presented an observation of the direct interaction between an erupting filament and a coronal hole. The eruption was closely associated with the initiation of a halo CME as well as its direction. They concluded that the large-scale structure of the CME was bounced against and then reflected away from the coronal hole along with the filament, and the eruptive filament was only a very small part of the CME. Jiang et al. (2008) also observed a direct interaction between a trans-equatorial jet and interconnecting loops (ILs). The jet originated from a flare and appeared to move outward along open field lines, but it passed so close to the ILs that its edge met one of the IL ends. As a result, the ILs began to erupt, weak brightening appeared at the interacting site, and a nearby dark feature was disturbed. Two CMEs were observed within 2 hr in association with the event. One was related to the flare and the jet, while the other was due to the IL eruption. These results suggest that a solar flare can not only trigger a CME but also simultaneously trigger an IL eruption via interactions with a jet, and so can lead to two interdependent CMEs, i.e. a sympathetic CME pair physically connected by the jet/IL interaction. Based on multi-wavelength observations of an event of 2002 March 17 and magnetic field extrapolation, Yan et al. (2006) found that the type III electron beams propagate in the interface region between the ascending CME and the neighboring open field lines. Due to the development of the CME, this region progressively becomes more highly compressed.

Shen et al. (2010) revisited the issue of the influence of coronal holes (CHs) on CMEs in causing solar energetic particle (SEP) events. They extrapolated the coronal magnetic field, define CHs as the regions consisting of only open magnetic field lines and perform an analysis of 76 events. Their result confirms the previous conclusion that CHs did not show any evident effect on CMEs in causing SEP events.

6.2 Triggering Mechanism

As concerns the triggering mechanism of CMEs, Chinese colleagues have also made essential contributions. Zhang & Low (2005) provided a hydromagnetic view of the CMEs as the products of continual magnetic flux emergence and interplays between magnetic reconnection and approximate magnetic-helicity conservation in the corona. They proposed that the helicity accumulation has played a central role in CME dynamics. Zhang et al. (2006b) first pointed out that, for a given boundary flux distribution, there is an upper bound on the total magnetic helicity that force-free fields can contain. Once the stored magnetic helicity exceeds this upper bound, an eruption becomes unavoidable. Thus they concluded that CMEs are the unavoidable products of magnetic helicity accumulation in the corona. Their study regards the formation of magnetic flux ropes and CME eruptions as natural and unavoidable results of coronal evolution. Based on observations, Chen & Shibata (2000) ran a numerical simulation and proposed a mechanism of CME triggering by emerging flux. Xu et al. (2005) made a parametric survey of the triggering agent and found that whether a CME can be triggered depends on both the amount and the location of the emerging flux, in addition to its polarity orientation. Zhang et al. (2006c) and Zhang & Wang (2007) explored their early finding that there would exist double current sheets resulting from the MHD catastrophe of coronal flux rope in
a quadrupolar magnetic field: a horizontal one above the flux system and another vertical one under the flux rope. They further proposed a two-current-sheet reconnection model of an interdependent flare and CME. This numerical model exhibits characteristics of both the magnetic breakout model for CME initiation and the standard flare model for flare occurrence. Zhang et al. (2008c) made a statistical survey of 189 CME-source regions, 46 active regions and 15 newly emerging active regions. They found that 60% of the CME-source regions have a flux increase during the 12 h before the eruption and 40% show a magnetic flux decrease. They conclude that the relationship between CMEs and flux emergence is complicated and that flux emergence is only one of the triggers for CMEs.

Anomalous resistivity is critical for triggering fast magnetic reconnection in the nearly collisionless coronal plasma. However, the mechanism for the production of anomalous resistivity and its evolution is still an open question. Wu et al. (2010) numerically solved the one dimensional Vlasov equation to study the relationship between anomalous resistivity and the bulk drift velocity of electrons in the reconnecting current sheets. They found that if drift velocity is slightly larger than the threshold of ion-acoustic instability, the anomalous resistivity due to the wave-particle interactions is enhanced by about five orders of magnitude as compared with classic resistivity due to Coulomb collisions. They pointed out that considering the final velocity of electrons ejected out of the reconnecting current sheet decreases with the distance from the neutral point, the anomalous resistivity should also decrease with the distance from the neutral point, which is favorable for the Petschek-like reconnection to take place.

7 ACTIVE REGIONS AND THE CORONA

The origin of the solar wind in solar coronal holes has long been unclear. Tu et al. (2005) did an important study and found that the solar wind starts flowing out of the corona at heights above the photosphere between 5 Mm and 20 Mm in magnetic funnels. Based on these results, they proposed a model for understanding the origin of the solar wind. Through an analysis of an image sequence obtained by the X-Ray Telescope onboard the Hinode spacecraft, Guo et al. (2010c) found that quasi-periodic outflows are present in the boundary of an active region. The flows are observed to occur intermittently, often with a period of 5–10 min. The speed distribution peak of the projected flow is around 50 km s\(^{-1}\). This sporadic high-speed outflow may play an important role in the mass loading process of the slow solar wind.

Based on observed vectormagnetograms, Zhao et al. (2008) determined the three-dimensional (3D) topology skeleton of the magnetic fields in the active region NOAA 10720 (Fig. 9). The skeleton consists of six 3D magnetic nulls and a network of corresponding spines, fans, and null-null lines. For the first time, they have identified a spiral magnetic null in the Sun’s corona. The magnetic lines of force are twisted around the spine of the null, forming a “magnetic wreath” with an excess of free magnetic energy and resembling observed brightening structures at EUV wavebands. They suggested that the magnetic wreath associated with the 3D spiral null is likely an important class of the physical entity of flux ropes. Feng et al. (2007a,b) made an automated loop detection in an active region and obtained the 3D coronal loops stereoscopically, and then compared them with the magnetic field lines extrapolated from the linear force-free field model. They found that a nonlinear force free field was required to describe the magnetic property in that active region.

Guo et al. (2010b) presented a statistical study to show how the quantified magnetic complexity of active regions (ARs) evolves in the 23rd solar cycle. A structural parameter \(dE\) is used to quantify the magnetic complexity of ARs. They found that complex ARs are scattered over solar cycle 23 and there is some asymmetry in the northern and southern hemispheres.

Zhang et al. (2008b) studied the rapidly rotating polarities in an extensive \(\delta\) sunspot in the active region NOAA 10486, which produced several powerful flare-CMEs. They found that these polarities rotated more than 200° for six days, and the helicity injection inferred from such rotational motion is
Fig. 9  Skeleton evolution in the interval from the pre-state to the recovery phase of a flare/CME. Different topologies are drawn in distinct colors (Zhao et al. 2008).

about $-3.0 \times 10^{13}$ Mx$^2$. Su et al. (2010) presented an important and quite controversial observational property of penumbral filaments, that they may exhibit twisting motions and change their chirality. Their results indicate that penumbral filaments are more inclined to be twisted magnetic flux tubes in nature. In addition, the global twist of sunspot magnetic fields obtained from Hinode high-resolution Vector Magnetograms also exclude the origin of penumbral filaments from the plasma convection in penumbral gaps with the field being absent (Su et al. 2009a or Su et al. 2009b).

The heating of the corona is still a key issue for understanding the nature of nonequilibrium and nonstatic dynamic plasma in the corona. There is increasingly evidence in both theories and observations (e.g. Tomczyk et al. 2007) that Alfvén waves (AWs) can transport sufficient energy to keep the corona at the observed high temperature. However, there still is a key difficulty that is how to convert the wave energy into the kinetic energy of plasma particles and how to form the observed fine structures in the corona. Theoretical works suggested that the AWs emitted from the solar surface could be converted into small-scale kinetic AWs (KAWs) when propagating outward...
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8 SMALL SCALE ACTIVITIES

Owing to high resolution observations made both by space-based and ground-based telescopes, solar small-scale activities (SSAs), such as Ellerman bombs (EBs) and microflares (MFs), have recently become hot topics in solar physics. This is because the SSAs have relatively simple structures and so are easy to study, but their physical mechanisms are more or less similar to major, complicated eruptions, such as major flares and coronal mass ejections. So the study of SSAs will help to understand the physical nature of major eruptions. Moreover, some studies show that an SSA may contribute, to some extent, to the heating of the solar atmosphere, which is still a puzzling problem in solar physics.

Using the high-resolution spectral data obtained with THEMIS on 2002 September 5, the characteristics of 14 well-observed EBs (Fang et al. 2006a) and five well-observed MFs (Fang et al. 2006b) have been analyzed. With Hα and CaII 8542 Å lines, for the first time both thermal and non-thermal semi-empirical atmospheric models for EBs and MFs are computed. The common characteristic is the heating in the lower chromosphere and the upper photosphere for EBs and in the lower chromosphere for MFs. The temperature enhancement is about 600–1300 K for EBs and about 1000–2200 K for MFs. An interesting micro two-ribbon flare was observed and analyzed by Fang et al. (2010). They found that the energy can even be as high as $10^{29}$ erg. These results imply that EBs and MFs can probably be produced by the magnetic reconnection in the solar lower atmosphere. The difference in triggering mechanisms between EBs and chromospheric MFs is that the reconnection for the former is in the photosphere, but that for the later is in the chromosphere. The results from 2D numerical simulations indicate that the lifetime, temperature enhancement, energy and dynamical process, etc., of both EBs and MFs can be well explained by the magnetic reconnection in the solar lower atmosphere (Chen et al. 2001; Jiang et al. 2010; Xu et al. 2011). Li et al. (2007c) studied the response of the chromosphere and corona to twelve small emerging flux events in Hinode observations. It was shown that even though the average separation of the two polarities and lifetime of these emerging flux regions were only 3.2′′ and 40 min, respectively, all these regions show corresponding enhanced emission in the Ca II H line and soft X-rays, indicating that these small-scale and short-lived emerging flux events heat the chromosphere and the corona to some extent.

Using the Hinode/EIS spectral data, Chen & Ding (2010) found that the explosive evaporation can be detected even in a microflare, suggesting that similar dynamic processes may exist in events with very different magnitudes. Chen & Priest (2006) performed MHD numerical simulations of magnetic reconnection, where the effect of five-minute solar p-mode oscillations was examined. UV emission lines were synthesized on the basis of numerical results in order to directly compare with observations. It was found that several typical, puzzling features of the Transition-Region Explosive Events with impulsive bursty behavior can only be explained if there exist p-mode oscillations and
the reconnection site is located in the upper chromosphere at a height range of around 1900 km < h < 2150 km above the solar surface.

Using the data from the X-ray Telescope (XRT) onboard Hinode and TRACE, Li & Li (2010) analyzed 48 X-ray transient brightenings (XTBs) and 237 EUV transient brightenings (ETBs) to study the connection between them. They found that only 20% of the ETBs have corresponding XTBs. This is probably due to the small amount of energy released, which is not enough to heat the plasma to coronal temperatures to produce X-ray emission, but these small ETBs may significantly contribute to the coronal heating.

Using the high-resolution polarimetric observations obtained by the SP onboard Hinode, Zhang et al. (2009a) studied the relationship between granular development and magnetic field evolution in the quiet Sun. Their results indicated that granules and small-scale magnetic fluxes influence each other: a granule develops and splits non-symmetrically while flux emerges at an outer part of the granular cell; when magnetic flux cancellation occurs in a granular cell, the granule shrinks and then disappears; magnetic flux emergence in a cluster of mixed polarities is detected at the position of a granule as soon as the granule breaks up.

Jiang et al. (2007c) analyzed multi-wavelength observations of three surges with a recurrent period of about 70 min in Hα, EUV, and soft X-ray, which occurred in a quiet-sun region on 2000 November 3. These homologous surges were associated with small flares at the same base, but their exact footpoints were spatially separated from the flare. They noticed that each surge consisted of a cool Hα component and a hot EUV or soft X-ray component, which showed different evolutions not only in space but also in time. The EUV jets clearly showed twisting structures, and appeared to open to space. The Hα surges, however, were smaller and only traced the edges of the jets. The surge activities were closely associated with two emerging bipoles and their driven flux cancellations at the base region, which were consistent with the magnetic reconnection surge model.

9 SOLAR ACTIVITY AND ITS PREDICTIONS

In order to describe the cyclic behavior of solar full-disk activity, Li et al. (2008) proposed a new concept, i.e. a “full-disk activity cycle,” which consists of two successive normal cycles: a high-latitude activity cycle following a low-latitude activity cycle. The new concept tells the cyclical evolution of the solar full-disk magnetic activity, showing how, when, and where magnetic polarity reversal takes place. In addition, the new concept clearly indicates that the so-called extended activity cycle is actually part of a full-disk activity cycle.

Goel & Choudhuri (2009) investigated the hemispheric asymmetry of solar activity during the last century and the solar dynamo. They found that the hemispheric asymmetry of the polar field in different solar minima has a reasonable correlation with the asymmetry of the next cycle, and that the theoretically computed asymmetries of different cycles compare favorably with the observational data. Li et al. (2009d) investigated the hemispheric sunspot activity of long-term hemispheric sunspot activity. It was found that sunspot activity is asymmetrically distributed in the hemispheres, but the largest hemispheric diversity usually does not appear around the maximum time of a cycle, and that there was a systematic time lag or lead (phase shift) between northern and southern hemispheric solar activity in a cycle. About an eight-cycle period was inferred to exist in such phase shifts. The activity on the Sun may be governed by two different and coupled processes (Li et al. 2009c, 2010b). Latitudinal migration of sunspot groups and filaments does asynchronously occur in the northern and southern hemispheres, and there is a relative phase shift between the paired wings of their butterfly diagrams in a cycle, making the paired wings spatially asymmetrical on the solar equator. It is inferred that hemispherical solar activity strength should evolve in a similar way within the paired wings of a butterfly diagram in a cycle (Li et al. 2010c). It is interesting to note the cyclical behavior of CMEs. Li et al. (2009b) found that there is surprisingly no equatorward drift of CMEs at low latitudes (thus, no “butterfly diagram”) and no poleward drift at high latitudes, and no antiphase
relationship between CME activity at low and high latitudes. This suggests that there is possibly a single so-called large-scale activity cycle in CMEs.

Taking into account the solar surface’s differential rotation has revealed two persistent active longitudes of sunspots and solar soft X-ray flares, separated by about 180 degrees on the Sun. Strong active regions occur more preferentially at these active longitudes (Zhang et al. 2007b, 2008a). Moreover, Chen et al. (2011) found that the longitude distribution of solar superactive regions is significantly non-axisymmetric, and about 75% of super ARs are concentrated at the two active-longitudes with separations of 160°–200°. These observational facts are consistent with those predicted by the framework of the non-axisymmetric solar dynamo model (Jiang & Wang 2007).

The continuous wavelet transformation is proposed to study the temporal variations of the rotational cycle length (Li et al. 2011b,c). The rotational cycle length of the Sun is found to have a secular trend, which may be related to the variation of sunspot activity over the long run.

Predicting solar activity, especially the amplitudes and lengths of 11-year solar cycles, is an important task in solar physics and in space weather. Various methods have been proposed and discussed during recent years. They can be divided into two categories: statistical and precursor-based methods. Du et al. (2008) proposed a running average method to predict the solar activity by using the varying trend of the running correlation coefficient between the solar cycle amplitudes and the max-max cycle lengths. However, their prediction of the peak sunspot number of cycle 24 (140) is certainly too high. Many facts imply that solar cycle 24 will be an anomalously low activity cycle (Li 2009; Fang & Li 2011). However, considering the long-term running of the timescales of both the Gleissberg period and millenniums, the extended solar activity minimum is logical (Li et al. 2011a). Xu et al. (2008) used the Empirical Mode Decomposition (EMD) and Auto-Regressive model to make a long-term prediction of sunspot numbers. The prediction for cycle 23 is reliable, but the prediction for the maximum amplitude of cycle 24 to be about 112 in 2011–2012 seems not good. Wang et al. (2009d) found that solar cycles 9, 11, and 20 are similar to cycle 23 in their respective descending phases. Using this similarity and the observed data of smoothed monthly mean sunspot numbers (SMSNs) for the descending phase of cycle 23, they predict the start of March or April 2008 for cycle 24, and the maximum SMSN of cycle 24, 100.2±7.5, to appear during the period from May to October 2012. Du & Wang (2010) reexamined the relationship between the maximum amplitude of mean sunspot number ($R_{\text{max}}$) in a solar cycle and the minimum one ($R_{\text{min}}$) in the preceding cycle. However, it is found that this relationship is not always effective for individual cycles (Du et al. 2009). Du & Wang concluded that the very low $R_{\text{min}}$ in cycle 23 does not infer a very weak cycle 24. Following the suggestion of Wilson et al. (1998), they used a bivariate-fit regression equation of the $R_{\text{max}}$ versus both the $R_{\text{min}}$ and the minimum smoothed monthly mean index to predict the $R_{\text{max}}$ for cycle 24 to be 88.3±15.3, which seems reliable.

Combining the support vector machine (SVM) and the K-Nearest Neighbors (KNN) analysis methods, Li et al. (2007f) proposed an SVM-KNN method to construct a solar flare forecasting model. The test results for solar cycle 23 indicate that the rate of correct predictions from the SVM-KNN method is higher than that from the SVM or KNN method.

The solar cycle is produced by a complex dynamo mechanism. Jiang et al. (2007a) modeled the last few solar cycles by feeding the observational data of the poloidal field at the minimum into their solar dynamo model. Their results fit the observed sunspot numbers of cycles 21–23 reasonably well and predict that cycle 24 will be about 30% weaker than cycle 23. Their dynamo model can well explain the correlation between the polar field at a sunspot minimum and its next cycle strength.

One of the most remarkable features of sunspot activity is the Maunder minimum - a period during 1645–1715 when very few sunspots were seen. Choudhuri & Karak (2009) proposed that the poloidal field at the end of the last sunspot cycle before the Maunder minimum fell to a very low value due to fluctuations in the Babcock-Leighton process. With this assumption, a flux transport dynamo model is able to explain various aspects of the historical records of the Maunder minimum remarkably well if one suitably chooses the parameters of the model to give the correct growth time.
10 DISCUSSION AND CONCLUSIONS

From the description above, one can see that recent solar physics research in Mainland China has rapidly developed. Important achievements have been obtained both in instrumentations and research works. Not only have the number of publications greatly increased, but the quality has also improved. However, there are still some problems that need to be solved. One problem is the lack of solar space facilities, which are needed even though we have many ground-based telescopes. Fortunately, China has now started several space projects dedicated to solar physics. Moreover, we have started the site survey to select the best site for future solar observations. If successful, then we are hoping to construct some large solar telescopes in the future. It should be mentioned that there are still several weaknesses of solar physics research in Mainland China, for instance, research studies on the solar interior, including helioseismology, dynamo, interior structure and dynamics, and so on, which are relatively weak. Luckily, the gradual improvement in the above weak areas is in progress.

International collaboration has been greatly developed in recent years and it is essential for the future development of solar physics in China. We have close collaborations with scientists in the United States, France, Germany, Japan, India, Russia, Korea and many other countries. In addition to scientist exchange, Chinese students are often sent to other countries to study and learn from foreign scientists. In particular, Indian colleagues first proposed, and then many colleagues supported organizing the first Asia-Pacific solar physics meeting, which was successfully held in March in Bangalore during 2011. The second one will be organized in China in 2013. We do hope that these international collaborations could be further developed.

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