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Commission 10: Solar Activity

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Abstract. Commission 10 aims at the study of various forms of solar activity, including networks, plages, pores, spots, fibrils, surges, jets, filaments/prominences, coronal loops, flares, coronal mass ejections (CMEs), solar cycle, microflares, nanoflares, coronal heating etc., which are all manifestation of the interplay of magnetic fields and solar plasma. Increasingly important is the study of solar activities as sources of various disturbances in the interplanetary space and near-Earth "space weather".

Over the past three years a major component of research on the active Sun has involved data from the RHESSI spacecraft. This review starts with an update on current and planned solar observations from spacecraft. The discussion of solar flares gives emphasis to new results from RHESSI, along with updates on other aspects of flares. Recent progress on two theoretical concepts, magnetic reconnection and magnetic helicity is then summarized, followed by discussions of coronal loops and heating, the magnetic carpet and filaments. The final topic discussed is coronal mass ejections and space weather.

The discussions on each topic is relatively brief, and intended as an outline to put the extensive list of references in context.

The review was prepared jointly by the members of the Organizing Committee, and the names of the primary contributors to the various sections are indicated in parentheses.

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1. Solar missions update (R.A. Harrison)

We are enjoying a golden age of solar space mission activities. The Solar and Heliospheric Observatory (SOHO), the solar physics flagship mission since 1995, has been complemented by the Transition Region And Coronal Explorer (TRACE) mission since 1998, and by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spacecraft since 2002. Until 2001, we also enjoyed a decade of observations from the Japanese Yohkoh spacecraft. The wealth of new data raised many new questions, and influenced the strategy and planning of future missions aiming at the following:

much higher spatial and temporal resolution than currently available; in situ measurements of the innermost heliosphere and even the corona; high latitude imaging and spectroscopy (i.e. out of the ecliptic); out of Sun-Earth line observation; and 3-dimensional views of the Sun. Some of these aims will be achieved with missions planned over the next three years. There are two next generation high-resolution missions: the Japanese Solar-B spacecraft, due for launch in 2006, and the NASA Solar Dynamics Observatory (SDO), due for launch in 2008. The NASA STEREO spacecraft, due for launch in 2006, will get us out of the Sun-Earth line, with a twin-spacecraft mission with both spacecraft in 1AU solar orbits, one leading the Earth and one lagging the Earth.

2. Solar flares (D.B. Melrose, A.O Benz & L. van Driel-Gesztelyi)

Over the period covered by this report the largest flare of the modern era occurred on 2003 November 4. The GOES detectors were saturated during the flare, but a magnitude X28 was estimated (a peak flux of 2.8 mW in the 1–8 Å band). The enhanced X-ray flux caused a substantial lowering of the D region of the ionosphere, suggesting an even higher magnitude of around X45 (Thomson, Rodger & Dowden 2004).

RHESSI data had a major impact on solar physics research over the three years. Some specific outcomes included the following. (1) The greatly improved spectral resolution (1 keV at low energies, $>$ 10 keV) allowed investigation of the energy partition in flares with much increased precision. Thermal and non-thermal phenomena were resolved more clearly (Alexander & Medcalf 2002; Krucker *et al.* 2002; Saint-Hilaire & Benz 2002, 2005; Hudson *et al.* 2003; Kontar *et al.* 2005; Grigis & Benz 2005; Battaglia & Benz 2005). In two major flares it was found that the kinetic energy of the CME exceeded the energy in non-thermal electrons in the associated flare by about an order of magnitude (Emslie *et al.* 2004a). (2) An unexpected result was that the source of the 2.223 MeV (neutron-capture) gamma-ray line was found to be displaced from the hard X-ray emission (Hurford *et al.* 2003). Explanations in terms of different locations for the electron and ion acceleration (Emslie *et al.* 2004a) and in terms of two interacting loops (Yurchyshyn *et al.* 2004) were suggested. (3) Observations of the pair annihilation line at 511 KeV seem to require a substantial mass of material at transitional rather than coronal temperatures during the flare (Share *et al.* 2003). (4) A new class of hard X-ray sources imply the presence of exceptionally dense coronal loops (Veronig & Brown 2004). (5) Direct evidence was found for the formation of a current sheet with an initial downward motion preceding the expected upward expansion (Sui & Holman 2003). (6) Observations of the vertical motions associated with flares showed that cold upflows and hot downflows ('warm rain') can occur simultaneously (Teriaca *et al.* 2003).

Observations of flares at other wavelengths with other new instruments also led to new results. Radio data with much improved resolution at high frequency became available with the Siberian Solar Radio Telescope at 5.7 GHz, with the Solar Submillimeter-wave Telescope (SST) at 212 GHz and 405 GHz in the Argentinian Andes and with KOSMA in the submillimeter range in the Swiss Alps. Results included the detection of short duration pulses at $<$100 ms in the submillimeter range (Raulin *et al.* 2003) and with shorter duration in the microwave range (Altyntsev *et al.* 2003; Chernov *et al.* 2003), and the identification of a new component of flare emission at terahertz frequencies (Kaufmann *et al.* 2004). Optical data from THEMIS and SOHO showed supersonic downflows preceding a flare by up to 8 hours (Meunier & Kosovichev 2003). THEMIS data also provided evidence for the expected return current in the chromosphere (Hénoux & Karlicky 2003) resulting from the precipitation of energetic electrons. For the first time flares were also observed in total solar irradiance by the SORCE satellite. Woods *et al.* (2004) measured the total flare irradiance to exceed the soft X-ray emission ($<$27 nm) by a factor of five. These numbers leave a gap in the standard scenario of the chromospheric response to precipitating non-thermal particles; moreover, a test of the Neupert effect (a causal relation between the thermal soft X-ray flux and the non-thermal hard X-ray flux) led to equivocal results (Veronig *et al.* 2005).

The issues concerning microflares and nanoflares have not been resolved, and moreover the term 'nanoflare' is used with two somewhat different meanings. Microflares are active-region brightenings in soft X-rays and they have photospheric signatures in the form of flux emergence and accompanying Hα brightenings (Shimizu *et al.* 2002). Microflares in hard X-rays were found to originate from active regions (Krucker *et al.* 2002), but their observed rate does not significantly contribute to the heating of the active region corona (Benz & Grigis 2002). The term 'nanoflare' refers both to the 'smallest flare in quiet region', and 'unobservable small flare in active region loop'. Yamauchi *et al.* (2005) argued that cancellation of photospheric magnetic fields results in transition region supersonic jets and microflares, and this provides support for coronal heating by jets and shocks associated with nanoflares (Ryutova & Tarbell 2003; Markovskii & Hollweg 2004). However, whether or not heating is due to nanoflares is uncertain: the estimated heat input from small flares is subject to observational biases (Aschwanden & Parnell 2002), and is not well known (Benz & Krucker 2002).

Space-based observations in the visible range show that white light flares (WLFs) are more common than previously thought, and are not a result of 'Big Flare Syndrome' (Kahler, 1982). Matthews *et al.* (2003) compared 28 WLFs observed by Yohkoh with a sample of non WLFs and found, in addition to the well documented correlation with HXRs, WLFs show a strong correlation with coronal over-pressure, indicating the presence of a thermal component. Metcalf *et al.* (2003) found that the brightest WL kernels and associated HXR sources are in ribbons spatially associated with magnetic separatrices. Ribbons in the NIR ($1.56\,\mu$m) were found to be both temporally and spatially correlated with HXR emission during the impulsive phase (Xu *et al.* 2004). Some progress has been made in understanding the heating of the atmosphere required to explain WLFs (Allred *et al.* 2005).

The statistics of flares has attracted attention. Time series of X-ray/EUV emission from coronae of magnetically active stars have also been interpreted in terms of superposed flares (Arzner & Güdel 2004). Proposed explanations for the solar flare power-law distribution include MHD-based avalanche models (Vlahos *et al.* 2002), and reconnection at many separators (Wheatland & Craig 2003). The flare waiting-time distribution is also found to be a power-law that varies with the solar cycle (Wheatland & Litvinenko 2002). Interestingly, observed flare statistics might also provide a method for flare prediction (Wheatland 2004).

Data relevant to acceleration mechanisms for the non-thermal electrons and ions was reviewed in detail early in the three-year period (Aschwanden 2002a). Various mechanisms continue to attract support: stochastic acceleration (Emslie *et al.* 2004b), acceleration associated with reconnection (Hamilton *et al.* 2005) and acceleration associated with unresolved shocks (Tanuma & Shibata 2005). It is still unclear where the bulk of the energetic particles associated with CMEs are accelerated: near the apparent source in the corona (Bieber *et al.* 2004) or at CME-associated shocks in the solar wind (Tsurutani *et al.* 2003).

3. Magnetic reconnection (I.J.D. Craig)

Magnetic reconnection continues to be the favored mechanism for explosively releasing magnetic energy in the atmospheres of solar-type stars. Theoretical developments over the past three years have emphasized the 3D topology of the reconnecting magnetic fields (Linton & Antiochos 2002; Longcope & Klapper 2002; Titov *et al.* 2003; Priest *et al.* 2003; Parnell & Galsgaard 2004). This led to dynamic models of spine and fan reconnection, a nomenclature based on the separatrix geometry of 3D magnetic nulls. A further type of merging – separator reconnection – which involves localized currents along the line joining two magnetic nulls, appears more closely related to the classical 2D picture. Exact dynamic models of all these reconnection processes are providing a self consistent platform for particle acceleration studies, avoiding the arbitrary field parameterizations of heuristic Sweet-Parker type models (Heerikhuisen *et al.* 2002).

There is a growing consensus on two aspects of reconnection. First, anomalous resistivity seems to be essential, with many authors now recognizing that it is the only way to localize the resistivity to allow fast reconnection (Uzdensky 2003). Second, forcing motions are the likely cause of the triggering of flares (Kusano *et al.* 2004; Birn *et al.* 2004), probably by emerging flux interacting with an existing magnetic structure. However, other aspects remain controversial. In particular, claims have been made for "separator reconnection" (Longcope *et al.* 2005) at the expense of null-point merging (Antiochos *et al.* 2002), but the real nature of the mechanism remains unclear. Resistive MHD treatments have been extended to include Hall current and electron inertial effects, within a generalized Ohm's law, but claims for greatly enhanced reconnection rates arising from Hall currents (Dorelli 2003) are controversial. It is not clear, at least in driven reconnection models, whether the problem of unphysically large electric current densities at the reconnection site – a recurring problem in classical MHD – is eased or worsened by Hall effects (Watson & Porcelli 2004).

Observational evidence for reconnection has continued to mount. One observational surprise is that inferred outflow jets from coronal reconnection sites are about an order of magnitude smaller than the Alfvénic speeds expected on conventional resistive models (Asai *et al.* 2004). Other dissipation mechanisms, such as provided by the plasma viscosity, could well be involved in limiting the speed of the reconnection exhaust. What can almost certainly be said is that extra physical ingredients need to be incorporated into resistive MHD models if a convincing theoretical description of reconnection is to be achieved.

4. Magnetic helicity (L. van Driel-Gesztelyi)

Observational and theoretical investigation of magnetic helicity has emerged as a new major research field. Magnetic helicity measures intrinsic properties of magnetic flux tubes: shear, linking, kinking, twist and handedness. Its importance is due to it being conserved in resistive MHD, and in particular during magnetic reconnection. It is thought to be generated by the solar dynamo, to emerge in twisted magnetic flux (Démoulin *et al.* 2002a,b; Green *et al.* 2002; Nindos & Zhang 2002; Moon *et al.* 2002; Démoulin & Berger 2003; Nindos *et al.* 2003; Chae *et al.* 2004), and to be carried away in CMEs (Mandrini *et al.* 2005). The sign of helicity generation is cycle-independent, and conservation of helicity puts tight constraints on solar dynamo models (Blackman 2003; Brandenburg *et al.* 2005). However, observational limitations and numerical simulations (Gibson *et al.* 2004) suggest that we may be underestimating the photospheric helicity flux, and several improved techniques have been suggested (Kusano *et al.* 2002; Welsch *et al.* 2004; Longcope 2004; Pariat *et al.* 2005). Most of magnetic helicity is injected into the corona in active regions since the quiet Sun's contribution was shown to be negligible (Welsch & Longcope 2003). In relation to CMEs there is statistical evidence that helicity is important: the preflare value of coronal helicity is smaller in big flares without CMEs than in big flares with CMEs (Nindos & Andrews 2004).

5. Coronal loops and heating (J.A. Klimchuk)

The past three years have seen major progress in understanding coronal loops and their heating (Walsh & Ireland 2003; Aschwanden 2004a; Klimchuk 2004). Loops observed in hot (>2 MK) emissions are consistent with the older picture of coronal loops as static structures heated in a quasi-steady fashion, but most loops observed in warm ($\sim$1 MK) emissions are inconsistent with this interpretation (Winebarger, Warren & Mariska 2003;

Patsourakos, Klimchuk & MacNeice 2004). This has led to a new picture in which loops are bundles of unresolved, impulsively-heated strands (Warren, Winebarger & Hamilton 2002; Mendoza-Briceno, Erdelyi & Sigalotti 2002; Warren, Winebarger & Mariska 2003; Spadaro *et al.* 2003; Cargill & Klimchuk 2004; Testa, Peres & Reale 2005; Patsourakos & Klimchuk 2005). The cooling of the strands implies that loops should be visible over a wide range of temperatures, but there is disagreement about what the observations actually show (Schmelz 2002; Schmelz *et al.* 2003; DelZanna & Mason 2003; Nagata *et al.* 2003; Schmieder *et al.* 2004; Winebarger & Warren 2005). This sparked a debate about the ambiguities and uncertainties inherent in the filter-ratio technique commonly used to infer temperatures (Martens, Cirtain & Schmelz 2002; Schmelz 2002; Aschwanden 2002b; Noglik, Walsh & Ireland 2004). Loops can also be dynamic when the heating is perfectly steady, as long as it is highly concentrated near the footpoints. A phenomenon called "thermal non-equilibrium" produces evolving condensations (Karpen *et al.* 2003; Mueller, Hansteen & Peter, 2003; Mueller, Peter & Hansteen 2004) that may explain counterstreaming motions often observed in prominences (Lin *et al.* 2003).

Several ideas were pursued concerning the mechanism of heating, most involving some form of magnetic reconnection at current sheets. Current sheets are expected to exist (1) at the interfaces between the 10s to 100s of elemental magnetic flux tubes that must be contained within a single coronal loop (Priest, Heyvaerts & Title 2002), and (2) at magnetic separators (Longcope & Klapper 2002), either dense concentrations of separators in regions of highly mixed magnetic polarity (Beveridge, Longcope & Priest 2003) or isolated, large-scale separators associated with interconnecting active regions (Longcope *et al.* 2005). The reconnection may be initiated by the secondary instability (Dahlburg, Klimchuk & Antiochos 2005), which switches on when the misalignment of tangled elemental flux tubes reaches the value predicted long ago by simple energy balance considerations (the so-called "Parker angle"). Studies of active regions (Gudiksen & Nordlund 2002, 2005; van Driel-Gesztelyi *et al.* 2003; Démoulin *et al.* 2003; Lundquist *et al.* 2004; Mok *et al.* 2005) and the global Sun (Schrijver *et al.* 2004) support the basic idea of heating at current sheets and seem to rule out waves as a dominant heating mechanism in the corona. Heating associated with the internetwork field (INF) – a small-scale, mixed-polarity field of substantial magnitude that is generated by near-surface compressible convection – may be important (Bercik *et al.* 2005).

The nascent discipline of coronal seismology continues to grow. The observed damping of loop oscillations can be used to infer the temperature, density, and magnetic field strength of loops as well as the values of important transport parameters, such as the coefficients of shear viscosity and thermal conduction (DeMoortel *et al.* 2002; Ofman & Aschwanden 2002; Schrijver, Aschwanden & Title 2002; Goossens, Andries & Aschwanden 2003; Marsh *et al.* 2003; Aschwanden 2004b; DeMoortel & Hood 2004; Klimchuk, Tanner & DeMoortel 2004). Despite the encouraging progress over the past three years in understanding coronal loops and coronal heating, much more remains to be done.

6. The magnetic carpet (K.J. Schrijver)

Over the past few years, it has become increasingly clear that essentially all of the magnetic flux outside active regions emerges and cancels locally. New flux emerges into the 'magnetic carpet' in quiet Sun in ephemeral bipolar regions (with fluxes of order 10^{20} Mx). There in increasing evidence that much of this flux is generated by a local turbulent dynamo on a continuum of strengths and length scales. There is a link to the global cyclic dynamo, however, because the overall rate at which ephemeral regions emerge varies with the solar cycle. Interestingly, the cycle of emergence of ephemeral regions precedes the sunspot cycle by 0.5–1.5 yrs. Further evidence for a link to the global dynamo is that there is also a weak preference in the orientation of the bipole axes of ephemeral regions that agrees with that of the large active regions, and a frequency distribution of fluxes that appears to be an extension of the active-region spectrum (Hagenaar *et al.* 2003). The result of this continual injection of ephemeral-region flux is that all of the quiet-Sun flux is replaced within a matter of at most a few days (Hagenaar *et al.* 2003). The frequent injection of flux into the quiet Sun in ephemeral regions is responsible for the appearance of the magnetic and chromospheric network patterns, with a field connectivity above it that is being studied in terms of its topological features, i.e., (surface and coronal) null points, spines, fans, and trunks formed by converging separators (Schrijver & Title 2002, Beveridge, Longcope & Priest 2003, Longcope *et al.* 2003).

The flux spectrum is determined in part by fragmentation rates (Parnell 2002), which can dominate coagulation by more than what the magnetochemistry model predicts within active regions (Abramenko & Longcope 2005). The topology of the quiet-Sun coronal field is dynamic with the survival time of any magnetic connection approximately 1.4 hr (Close *et al.* 2003).

Other related developments in our understanding of the small-scale structures include the following: (1) In the low corona over quiet Sun is a domain where the plasma β changes intermittently from greater than unity to less than unity, with 30% of the corona up to 25 Mm above the chromosphere having $\beta > 1$ (Schrijver & Van Ballegooijen 2005), so that one needs to allow for non-force free conditions within the coronal volume up to at least a few emission scale heights. (2) At an angular resolution of an arcsecond or better another component of the Sun's magnetic carpet is revealed: the internetwork field (INF) consisting of a rapidly evolving pattern of mixed-polarity fields, with typical strength $\sim$5–50 G (Domínguez Cerdeña *et al.* 2003, Sánchez Almeida *et al.* 2003), and the strongest field, 130 G, in the granular downflow lanes (Trujillo Bueno *et al.* 2004). (3) The INF may have field strengths up to a kilo-gauss in small bundles with fluxes of 10^{16}–10^{18} Mx, (Domínguez Cerdeña *et al.* 2003, Sánchez Almeida *et al.* 2003). (4) The INF may connect to some 30% of the coronal flux, rather than residing under the magnetic canopy (Schrijver & Title 2003). (5) Recent simulations of small-scale magnetoconvection suggest that dynamo action occurs in the near-surface layers of solar and stellar convective envelopes (Bercik *et al.* 2005), but it is not clear how much of the magnetic carpet is powered by local dynamo action.

In summary, there is observational and numerical evidence for magnetic field generation in both the near-surface layers and a deep-seated global dynamo, resulting in bipolar magnetic regions with fluxes ranging over about six orders of magnitude.

7. Filaments (L. van Driel-Gesztelyi)

Recent progress has been in understanding the details of the mechanism that allows cool, dense filaments or prominences to form in the hot, dilute corona through the thermal non-equilibrium mechanism in long coronal flux tubes and in sheared arcades (Karpen *et al.* 2003; Aulanier *et al.* 2002). Recently, Lites (2005), using photospheric vector magnetograms, found concave-up geometry below narrow, low lying filaments, consistent with the existence of dips in a global flux rope geometry, as predicted more than a decade ago by van Ballegooijen & Martens, and being consistent with non-LTE radiative transfer computations (Heinzel *et al.* 2005). Regarding more local features, various magnetostatic models recently predicted that the magnetic field in filament lateral extensions (known as barbs) should also be dipped (Aulanier & Démoulin 1998; Aulanier & Schmieder 2002; van Ballegooijen 2004; Régnier & Amari 2004). The dips are located above secondary photospheric inversion lines around minority polarity magnetic elements. This has been supported by some line-of-sight magnetograms (Zhong *et al.* 2003; Chae *et al.* 2005), but this issue is still being debated (Lin *et al.* 2005a,b).

Studies using the spectrometers SUMER and CDS aboard SOHO (Cirigliano *et al.* 2004) and the imagers TRACE and EIT provide information on the plasma surrounding a filament, where the temperature must increase from 5000 K to 1 MK similar to the transition region. A notable feature is that EUV lines located shortward of 912Å (the hydrogen Lyman-continuum head) appear dark on the disk and seem to be more extended as compared to their Hα counterparts. Two explanations for the intensity reduction are: Lyman continuum absorption (Schmieder *et al.* 2003); absorption and volume blocking assuming the EUV filaments are at high altitudes (Anzer & Heinzel 2003). Two possible geometries can account for these processes, though both possibilities are still debated : radiative transfer models result in cool clouds located at high altitude all around filaments (Heinzel *et al.* 2003; Schmieder *et al.* 2004; Schwartz *et al.* 2004); 3D magnetostatic models rather predict low lying structures associated with magnetic dips (Aulanier & Schmieder 2002). An implication is that the filament mass is underestimated by a factor of two using the Hα observations (Schwartz *et al.* 2004).

8. Coronal mass ejections (N. Gopalswamy, R.A. Harrison & J.-X. Wang)

The study of coronal mass ejections (CMEs) has become one of the principal areas of solar research (Lin *et al.* 2003; Gopalswamy 2004; Zhang & Low 2005; Dere *et al.* 2005). About 10,000 CMEs have been observed by coronagraphs, notably on SOHO and, since 2003, with the Solar Mass Ejection Imager (Eyles *et al.* 2003).

The large number of CMEs allows statistical analysis. For example, Yashiro *et al.* (2004) found that the average width and speed of CMEs increased from 47° and 300 km s^{-1} at solar minimum to 61° and 500 km s^{-1} near solar maximum; also, the average apparent speed of halo CMEs (957 km s^{-1}) is twice that of normal CMEs (428 km s^{-1}), and most slow CMEs ($V < 250$ km s^{-1}) show acceleration whereas most fast CMEs ($V > 900$ km s^{-1}) show deceleration. There are analogous data on the kinematics of CMEs (Vrsnak *et al.* 2004; Yurchyshyn *et al.* 2005). The latitude distribution of CMEs favors the equatorial region around solar minimum, with a high-latitude, prominence-associated CMEs being present near solar maximum (Gopalswamy *et al.* 2003a). The cessation of high-latitude CMEs is related to the solar polarity reversal (Gopalswamy *et al.* 2003b), and it also appears to modulate Galactic cosmic rays in the inner heliosphere (Lara *et al.* 2005). There are various correlations between CMEs and surface activity but cause and effect are not always clear. One close correlation is between Earth-directed CMEs and local brightening in EIT images (Zhou *et al.* 2003). There is also a close correlation between solar prominence events observed by the Nobeyama Radioheliograph and CMEs (Gopalswamy *et al.* 2003c). However, the correlations between filament eruptions and CMEs (Jing *et al.* 2004), and between M-class flares and CMEs (Andrews 2003) are not one-to-one. A controversial point is whether flare-associated and non-flare-associated CMEs have statistically different properties, with the latest study finding no significant difference (Vrsnak *et al.* 2005).

The temporal evolutions of CMEs was clarified through a detailed multi-wavelength study of a set of CMEs by Zhang *et al.* (2004), which included coronograph data down to 1.1 $R_\odot$ from the center of the Sun. They found a three-phase ascent: an initiation phase displays a gradual expansion in the CME loops at speeds < 80 km s^{-1}; an impulsive acceleration phase during which there is a sudden increase in the speed at 1.3–4.6 $R_\odot$;

and a propagation phase at near-constant speed. The peak acceleration of the CME coincides with the soft X-ray flux peak, implying that CME bulk acceleration and particle acceleration are coupled in the corona. However, evidence for lateral expansion of the CMEs studied at the lowest altitudes raises doubts about the back-projection of the higher altitude coronagraph data to the flare site, which topic is still being debated (Harrison 2005).

Coronal dimming in X-rays and EUV appears to occur in CME source regions in the low corona (Harrison 2005). Spectral analyses confirmed that the dimming are due to mass loss, rather than heating or cooling of plasma, consistent with a mass of order that in a CME being ejected from the low corona (Harrison *et al.* 2003). The dimming and projected CME onsets are consistent with one another (Harra & Sterling 2003; Howard & Harrison 2004), further supporting the correlation. A new type of dimmings involves the so-called EIT waves, which appear to propagate from flare/CME sites and often wrap around the solar globe (Biesecker *et al.* 2002; Chertok & Grechnev 2003). An early suggestion was that they are fast-mode MHD waves that propagate outward from the CME initiation site (Plunkett *et al.* 2002). A more detailed theory is now available (Chen *et al.* 2005). It is clear that these are not Moreton-like waves, and that the wave does not represent the footprint of the overlying, outwardly propagating CME.

In a recent review of the source regions for CMEs it was argued that the association of CMEs, flares and filament eruptions depends on the characteristics of the source regions (Schmieder & van Driel-Gesztelyi 2005). Another study (Zhou *et al.* 2005) identified four types of large-scale magnetic structures as CME-prolific: transequatorial magnetic loops, extended bipolar regions with either complex active regions or long filament inside, transequatorial filaments, and very long filaments between two extended bipolar regions.

9. Physical understanding of CMEs (J.-X. Wang & L. van Driel-Gesztelyi)

There has been significant progress over the past three years in the modeling of CMEs and of their cause and their effects. There is both theoretical and observational support for the helical kink instability being associated with filament eruptions and CMEs. MHD simulations show such eruption (Amari *et al.* 2003a,b; Fan & Gibson 2003; Török *et al.* 2004, Kliem *et al.* 2004). The initial exponential growth and subsequent linear rise of the flux rope are reproduced (Török & Kliem 2005; Fan 2005), and the results could also reproduce the 'failed filament eruption' (Ji *et al.* 2003). Observational evidence for exponential height growth in the low corona (Gallagher *et al.* 2003; Shanmugaraju *et al.* 2003; Goff *et al.* (2005); Williams *et al.* 2005) and development a helical shape during the eruption (Williams *et al.* 2005) is supported by more direct evidence that the kink instability is indeed the driver of a number of filament eruptions (Rust & LaBonte 2005). It was pointed out that the widely used α_{best} method underestimates the helicity (Leka *et al.* 2005), and localized active region flux ropes may carry greater that 2π winds, close to the threshold of kink instability 2.5–2.75 π (Török & Kliem 2002).

The role of helicity in CME initiation proved somewhat controversial. On the one hand, Nindos *et al.* (2003) computed the magnetic helicity injected by transient photospheric horizontal flows and concluded that discrepancies in the helicity budget of active regions are much smaller than reported in earlier studies, and Nindos & Andrews (2004) showed that active regions with lower helicity tend to produce fewer CMEs. Also, Wang *et al.* (2004) argued that the helicity pattern plays a key role in CME initiation, and that emerging flux with the opposite sense of helicity is important in initiating CMEs. On the other hand, Phillips *et al.* (2005) argued that eruption occurs at a fixed magnitude of free energy in the corona, independent of the value of helicity.

Magnetic reconnection in the wake of coronal mass ejections is an important ingredient in recent magnetically driven eruptive flare/CME models. Webb *et al.* (2003) found that many CMEs are followed by coaxial, bright rays suggestive of newly formed current sheets lasting for several hours and extending more than $5\,R_\odot$ into the outer corona. Ko *et al.* (2003) studied an event which started with the expansion of a magnetic arcade, developed into a CME, and left some thin streamer-like structures, plausibly associated with a reconnecting current sheet. On the other hand, evidence of the required reconnection-associated inflows has proved elusive (Chen *et al.* 2004). Gary & Moore (2004) described a case in which an initial quadrapolar reconnection remove the overlying magnetic field, allowing the filament to erupt. Reconnection thus occurs first, as proposed in magnetic breakout model, and as in a numerical simulation of a quadrapolar magnetic system (Zhang *et al.* 2005). MacNeice *et al.* (2004) presented simulations of the breakout process, including the initiation, the plasmoid formation and ejection, and the eventual relaxation of the coronal field to a more potential state; they also demonstrated that the breakout model can produce fast CMEs.

10. Space weather (N. Gopalswamy & J.-X. Wang)

Space weather is the variability in space environments, notably in the plasma speed and density, the magnetic field and in radiation. The extreme storms of October-November 2003 constitute one of the best examples of adverse space weather in the recorded history (Gopalswamy *et al.* 2005a). The effect of such extreme events on manned spacecraft is of particular concern, and unmanned spacecraft need to be put into safe mode (Barbieri *et al.* 2005) . There are much wider terrestrial implications associated with intense geomagnetic storms (Zhang *et al.* 2003; Forbes & St. Cyr, 2004; Huttunen *et al.* 2005; Gopalswamy *et al.* 2005b), some of which can last for months (Jackman *et al.* 2005; Rohen *et al.* 2005). Faster CMEs cause more intense storms (Yurchyshuyn *et al.* 2004; Srivastava & Venkatakrishnan 2004), and more intense SEP events (Kahler, 2005). Quantitative estimates of shock arrival times (Gopalswamy *et al.* 2005c; Schwenn *et al.* 2005) assume that CMEs propagate in isolation, decelerating due to the interplanetary drag (Chen & Krall 2003; Ganzalez-Esparzza *et al.* 2003), although it is known that mergers occur (Burlaga *et al.* 2003) and affect the arrival time (Manoharan *et al.* 2004). The structure of CMEs, including helicity (Green *et al.* 2003; Nindos & Andrews 2004; Mandrini *et al.* 2005), influences the impact on the Earth and depends on the phase of the solar cycle (Li & Luhmann, 2004).

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