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COMMISSION 10 SOLAR ACTIVITY

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TRIENNIAL REPORT 2006 - 2009

1. Introduction

Commission 10 deals with solar activity in all of its forms, ranging from the smallest nanoflares to the largest coronal mass ejections. This report reviews scientific progress over the roughly two-year period ending in the middle of 2008. This has been an exciting time in solar physics, highlighted by the launches of the *Hinode* and *STEREO* missions late in 2006. The report is reasonably comprehensive, though it is far from exhaustive. Limited space prevents the inclusion of many significant results. The report is divided into the following sections: Photosphere and chromosphere; Transition region; Corona and coronal heating; Coronal jets; flares; Coronal mass ejection initiation; Global coronal waves and shocks; Coronal dimming; The link between low coronal CME signatures and magnetic clouds; Coronal mass ejections in the heliosphere; and Coronal mass ejections and space weather. Primary authorship is indicated at the beginning of each section.

2. Photosphere and chromosphere (C. J. Schrijver)

2.1. *Quiet-Sun field within the photosphere*

The Solar Optical Telescope (SOT) on board the *Hinode* spacecraft provides an unprecedented combination of spatial resolution and continuity of observations. The SpectroPolarimeter focal-plane instrumentation exploits that to measure the polarization signals from the photospheric plasma. Lites *et al.* (2008) and Ishikawa *et al.* (2008) show direct evidence that much of the magnetic field in the quiet-Sun photosphere is essentially horizontal to the solar surface. This observation is the direct confirmation of the existence of the weak field for which less direct evidence had been found by Harvey *et al.* (2007), and contributes to Hanle de-polarization effects discussed by, e.g., Trujillo Bueno *et al.* (2004).

The nearly vertical component is found primarily in the downflow network of the granular convection, corresponding to the well-known network field. The horizontal field is mostly found in the interior of the convective cells. Despite this significant preference for a separation by upflow and downflow domains, flux has been observed to also emerge already largely vertical even within the interior of the granular convective cells (Orozco-Suarez *et al.* 2008). And, perhaps not surprisingly, the conceptually expected evolutionary pattern of emerging flux is also seen: Centeno *et al.* (2007) report on observations in which field is seen to first surface nearly horizontally and subsequently – as it is advected to the downflow lanes – rights itself to be nearly vertical.

Lites *et al.* (2008) measure the mean flux density of the horizontal field to be about five times higher than that associated with the nearly vertical field component. Interestingly, radiative MHD simulations of near-surface stratified convection by Schuessler and Voegler (2008) show a very similar orientation-dependent ratio for the field. Steiner *et al.* (2008) reach a similar conclusion based on their numerical experiments: they argue that the granular upflows allow field to be stretched horizontally, being advected from over the cell centers only slowly in the stagnating, overshooting, upper-photospheric flows. Both studies support the conclusion that near-surface turbulent dynamo action significantly contributes to the internetwork photospheric field. A study by Abbett (2007) elucidates how such a turbulent-dynamo field would connect sub-photospheric and coronal layers through a complex and dynamic chromospheric layer in between; work by Isobe *et al.* (2008) explores numerically the frequent reconnective interactions expected with the overlying chromospheric canopy field, suggesting that this and the associated wave generation may have significant consequences for atmospheric heating and driving of the solar wind.

2.2. *The solar dynamo(s): global and local aspects*

Ephemeral bipolar regions are at the small end of the active region spectrum. Their properties over the solar cycle are an extension of those of their larger counterparts: they follow the general butterfly pattern, and have the proper preferential orientation of their dipole axes relative to the equator, but with a spread about the mean that increases towards the smaller bipoles. In this, they are a natural extension of the active region population. Where they were known to differ from the large regions is in the fact that they are the first to appear and last to fade for a given sunspot cycle.

Now, work by Hagenaar *et al.* (2008) uncovers another distinct property of ephemeral regions: the emergence frequency decreases with increasing local flux imbalance (consistent with findings by Abramenko *et al.* (2006) and Zhang *et al.* (2006) who differentiated only coronal hole regions from other quiet-Sun regions). Hagenaar *et al.* (2008) find that the rate of flux emergence is lower within strongly unipolar network regions by at least a factor of 3 relative to flux-balanced quiet Sun. One consequence of this is that because coronal holes overlie strong network regions, there are fewer ephemeral regions, and therefore fewer EUV or X-ray bright points within coronal holes.

The ephemeral-region population thus takes an interesting position in the study of solar magnetic activity: with the smallest-scale internetwork field perhaps largely generated by a local turbulent dynamo (Schuessler & Voegler 2008), and with the active regions associated with a global dynamo action, the ephemeral region population has signatures of both. Voegler & Schuessler (2007) show that local dynamo action can lead to a mixed-polarity field similar to the flux balanced very-quiet network field. It remains to be seen what such experiments predict in case there is a net flux imbalance, i.e., a background 'guide field': are fewer ephemeral regions generated, or does reconnection with the background guide field cause fewer of them to survive the rise to the surface (see discussion by Hagenaar *et al.* 2008).

2.3. *Emerging flux: observations and numerical experiments*

Observations made with the *Hinode*-SOT show unambiguously that magnetic flux bundles that form active regions do not emerge as simply curved arches, but rather as fragmented collections of undulating flux bundles. Each bundle likely crosses the photosphere one or more times between the extremes of the emerging region (e.g., Lites 2008). This is likely the result of the coupling to the near-surface convective motions, and the difficulty of relatively heavy sub-photospheric material to drain from the dipped field segments. Reconnection between neighboring supra-photospheric flux bundles could pinch off the sub-photospheric mass pockets, thus allowing the field to rise into the corona. Radiative MHD simulations of emerging flux by Cheung *et al.* (2008) support this interpretation: they show the 'serpentine' nature of the emerging flux, with characteristics that resemble the observed patterns of emerging flux, flux cancellation with associated downflows, convective collapse into strong-field flux concentrations, and photospheric bright points. Note that an example of field dipping into sub-photospheric layers is also discussed by Abbett (2007).

2.4. *Upper-chromospheric dynamics: spicules and waves*

Spectacularly sharp Ca II-H narrow-band filter observations made both with *Hinode*-SOT and the Swedish Vacuum Solar Telescope reveal ubiquitous jet-like features (called spicules or fibrils) above the solar limb. The relatively long-lived, broad population among these (discussed by De Pontieu *et al.* 2007a) appear to be caused by acoustic shock waves propagating upward from the photosphere. These shock waves cause the chromospheric material to undulate with almost perfectly parabolic height-time profiles, and saw-tooth velocity patterns. These shock-induced fibrils occur both in plages and in quiet Sun.

A more enigmatic phenomenon is formed by the much finer and more transient population of hair-like high extension of the chromospheric plasma discussed by De Pontieu *et al.* (2007b). Their origin remains subject to debate, but their transverse displacements point to the ubiquitous existence of Alfvén-like waves propagating into the corona. This is the most direct observational evidence for the existence of such waves reported to date. The estimated power suffices to heat the quiet-Sun corona and power the solar wind: these waves have amplitudes of 10-25 km s^{-1} for periods of 100-500 seconds. Alfvén-like waves with similar periods have also been observed for the first time in coronal loops, using the CoMP instrument (Tomczyk *et al.* 2007).

3. **Transition region** (H. Peter)

The transition region from the chromosphere to the corona, originally thought of as a simple thin onion shell-like layer, is a spatially and temporally highly complex part of the solar atmosphere. So far we are missing a unifying picture combining the numerous phenomena observed in emission lines formed from a couple of 10 000 K to several 100 000 K. Some of the aspects are re-interpreted by Judge (2008), who attempts to explain the transition region as being due to cross-field conduction of neutral atoms. The emission measure increasing towards low temperatures and the persistent redshifts are two of the major observational facts to be explained. A collection of one-dimensional transient models (Spadaro *et al.* 2006) and a three-dimensional MHD model (Peter *et al.* 2006) gave quantitative explanations for this. In agreement with the latter model, Doschek (2006) could show that the bulk of the (low) transition region emission originates from small cool loops. Using rocket imaging data, Patsourakos *et al.* (2007) give further direct observational evidence for the existence of such small loop-like structures dominating the transition region emission.

The magnetic field has to connect the transition region structures down to the chromosphere, and in case they are part of hot coronal elements also to the corona (Peter 2007). However, correlations between the transition region and the photosphere cannot be identified in a unique way (Sánchez Almeida *et al.* 2007). Larger features in the photosphere, such as moving magnetic features, might well leave an imprint in the outer atmosphere (Lin *et al.* 2006). In general, the connection from the chromosphere to the transition region is quite subtle and hard to identify in observations (Hansteen *et al.* 2007). A new way to investigate the relation between transient events in the transition region and the chromosphere was presented by Innes (2008). She studied the chromospheric emission of molecular hydrogen near 111.9 nm during microflaring events and proposes that the (coronal) energy deposition in the microflare also heats the chromosphere and thus affects the opacity for molecular hydrogen lines.

The energy balance, one part being the heating process, is largely determining the pressure of the transition region and thus implicitly also the mass loading. Combining various models and observations, Aschwanden *et al.* (2007) argue that the bulk part of the heating is located deep down, basically reflecting an exponential decay of the heating rate with height, on average. As speculated earlier, Tian *et al.* (2008a) could now show that the persistent blue-shifts in upper transition region lines are not due to the solar wind outflow, but due to mass loading of loops. Recent Doppler shift observations with the Extreme ultraviolet Imaging Spectrometer (EIS; Culhane *et al.* 2007a) on board *Hinode* indicate that the redshifts are due to radiative cooling and subsequent bulk downflows within the loops (Bradshaw 2008).

New investigations of coronal moss, i.e., the (upper) transition region footpoint areas of large hot loops, show that in moss regions the temperature is inversely related to the density (Tripathi *et al.* 2006). Using comparisons with models, Warren *et al.* (2008b) show that in order to understand this moss within the framework of a steady uniform heating model, one needs to assume that the moss plasma is not fully filling the volume. However, it remains to be seen if such a static model is applicable at all, because one might suspect a spatially varying heating rate (see above), and if the assumption of static moss is justified.

Motivated by direct magnetic field measurements in the corona indicating the presence of Alfvén waves (Tomczyk *et al.* 2007) and observations with SOT on *Hinode* above the limb, McIntosh *et al.* (2008) re-interpreted the widths of transition region lines across the solar disk. They conclude that the present observations are consistent with a line-of-sight superposition of Alfvénic disturbances in small-scale structures. How this relates to the new finding of Doschek *et al.* (2007) that the (non-thermal) line widths are largest not in the brightest parts of an active region but in dimmer regions adjacent to bright loops remains to be seen. Doschek *et al.* (2007) find broad lines related to potential outflow locations, so maybe this problem hints to different acceleration and heating mechanisms in open and closed field regions. Another new difference between (globally) open and closed field regions, was proposed by Tian *et al.* (2008b), who find evidence that the expansion of transition region structures is more rapid in the coronal holes as compared to the quiet Sun. Dolla & Solomon (2008) analyzed line widths above the limb in order to determine the (kinetic) temperatures of minor ions in presumably open field regions. They find the smallest mass-to-charge-ratio ions to be the hottest at a given height, but their analysis remains inconclusive with regard to supporting or disproving the proposed heating by ion-cyclotron resonances.

While being in orbit nearly 13 years now, the instruments on board *SOHO*, SUMER in particular, still give numerous new valuable results on the transition region. The EIS instrument on board *Hinode* covers wavelengths around 17–21 nm and 24–29 nm. This mainly includes emission lines formed from 1 to several MK, but also a small number of lines from the transition region, and allows good density diagnostics (Feldman *et al.* 2008). Given the spectral range, the main science topics are grouped around active region phenomena, while the transition region can also be investigated (Young *et al.* 2007). Besides these instruments, which will provide the main source for observations of transition region lines in the coming years, rocket experiments complement these data.

4. Corona and coronal heating (J. A. Klimchuk)

The past two years have seen considerable progress in understanding the magnetically-closed corona and how it is heated. This short report highlights just some of the important contributions. Much effort has been devoted to determining the properties of the heating – how it varies in time and space and whether it depends on physical parameters such as the strength of the magnetic field and the length of field lines. Some studies have concentrated on individual coronal loops, while others have addressed active regions as a whole. These efforts have both clarified some issues and raised new questions.

Let us first consider distinct, measurable loops. A short history is useful. For many years after the *Skylab* soft X-ray observations, it was thought that loops are static equilibrium structures maintained by steady heating. Then came the EUV observations from *SOHO*-EIT and *TRACE*. These revealed that warm (~ 1 MK) loops are much too dense for static equilibrium and have super-hydrostatic scale heights. Modeling efforts showed that the excess densities and large scale heights could be explained by impulsive heating. Because of their temperature response, EIT and *TRACE* are sensitive to the loops when they are cooling by radiation, well after the heating has ceased. The problem is that loops are observed to persist for longer than a cooling time, so a monolithic model is not viable. This led to the suggestion that loops are bundles of thin, unresolved strands. The observed high densities, large scale heights, and long lifetimes can all be explained if the strands are heated at different times by a storm of nanoflares. Since the strands are in different stages of cooling, a range of temperatures should be present within the loop bundle at any given time. In particular, there should be a small amount of very hot (> 5 MK) plasma. See Klimchuk (2006) for a discussion of these points and original references.

Whether loops are isothermal or multi-thermal has been intensely debated over the past several years. Double- and triple-filter observations from *TRACE* seem to suggest that the most narrow loops are isothermal (Aschwanden 2008). However, it has been demonstrated that many different thermal distributions, including ones that are broad, can reproduce the observed intensities, even with three filters (Schmelz *et al.* 2007a; Patsourakos & Klimchuk 2007; Noglik & Walsh 2007). Spectrometer observations provide far superior plasma diagnostics. The results here are mixed. Studies made with *SOHO*-CDS continue to find evidence for both isothermal loops and highly multi-thermal loops (Schmelz *et al.* 2007b; Cirtain *et al.* 2007), while studies made with the new EIS instrument on *Hinode* find that loops tend to be mildly multi-thermal (Ugarte-Urra *et al.* 2008; Warren *et al.* 2008a). Where temporal information is available, there is clear evidence that the loops are evolving, but the evolution is generally slower than expected for radiative cooling. Loop lifetimes are extremely important and require further investigation. A loop bundle will be only mildly multi-thermal if the storm of nanoflares is short-lived; however, the observed lifetime of the loop will then be correspondingly short. If a loop is observed to persist for much longer than a cooling time (López Fuentes *et al.* 2007), then its thermal distribution is expected to be broad. More work is needed on whether the lifetimes and thermal distributions of loops are consistent. Finally, Landi & Feldman (2008) have found that one particular active region is dominated by three distinct temperatures, which would greatly challenge our understanding if correct.

Modeling the plasma properties of whole active regions is a relatively new endeavor. In addition to providing valuable information on coronal heating, these research models are the forerunners of eventual operational models for nowcasting and forecasting the solar spectral irradiance. This is of great practical value, since the irradiance controls the dynamics, chemistry, and ionization state of the terrestrial upper atmosphere and thereby affects radio signal propagation, satellite drag, etc. Active region models based on static equilibrium are able to reproduce the observed soft X-ray emission reasonably well, but they fail, often miserably, at reproducing the EUV emission. The model corona is too faint in the EUV (there are no warm loops) and the moss at the transition region footpoints of hot loops is too bright. Winebarger *et al.* (2008) have demonstrated that better agreement can be obtained in the core of an active region by using a combination of flux tube expansion and filling factors near 10%. Filling factors of this magnitude have been measured in moss with EIS (Warren *et al.* 2008b). Small filling factors are consistent with the idea of unresolved loop strands. Reale *et al.* (2007) have developed a new multi-filter technique using *Hinode*-XRT data that reveals considerable thermal structure on small but resolvable scales.

Active region models based on impulsive heating are in much better agreement with observations than are static models. In particular, the predicted coronal EUV emission is greatly enhanced (Warren & Winebarger 2007; Patsourakos & Klimchuk 2008a). The predicted moss emission is still too bright, but these models assume constant cross section flux tubes, and expanding tubes will improve the agreement, as they do for static models. It is also likely that the brightness of the observed moss is diminished by spicules and possibly by other cool absorbing material.

Nanoflare models predict that very hot plasma should be present throughout the corona, albeit in very small quantities (Klimchuk *et al.* 2008; this paper presents a highly efficient IDL code for modeling dynamic loops and is available upon request). The intensities of very hot spectral lines are expected to be extremely faint, due to the small emission measures and possible also to ionization nonequilibrium effects (Bradshaw & Cargill 2006; Reale & Orlando 2008). Measurable quantities of very hot ($\sim 10\,\mathrm{MK}$) plasma have been detected outside of flares by the *CORONAS*-F spectroheliometers (Zhitnik *et al.* 2006), *RHESSI* (McTiernan 2008), and XRT (Siarkowski *et al.* 2008; Reale *et al.* 2008). The derived differential emission measure distributions, DEM(T), are consistent with the predictions of nanoflare models. The DEM(T) derived from EIS spectra for $T \leqslant 5$ MK are also consistent with the predictions (Patsourakos & Klimchuk 2008b). Other tests of the nanoflare idea include emission line Doppler shifts, broadening, and wing enhancements that are associated with evaporating and condensing plasma (Patsourakos & Klimchuk 2006; Hara *et al.* 2008; Bradshaw 2008).

Information on the distribution of nanoflare energies can be inferred from the intensity fluctuations of observed loops (Parenti *et al.* 2006; Pauluhn & Solanki 2007; Parenti & Young 2008; Sarkar & Walsh 2008; Sakamoto *et al.* 2008; Bazarghan *et al.* 2008). Proper flares are known to have a power law energy distribution with an index < 2. Extrapolating to smaller energies implies that nanoflares cannot heat the corona, as first pointed out by Hudson (1991). However, it is now believed that the power law index for small events is > 2, though with a large uncertainty (Benz 2004; Pauluhn & Solanki 2007; Bazarghan *et al.* 2008). Furthermore, the subset of proper flares that are not associated with CMEs also have a power law index > 2 (Yashiro *et al.* 2006; see Section 6). Since the physics of eruptive events and non-eruptive events (nanoflares and confined flares) is likely to be much different, it is not surprising that they obey different power laws.

Thermal nonequilibrium, a phenomenon thought to be important for prominence formation (Karpen & Antiochos 2008), may also play an important role in ordinary loops. Loop equilibria do not exist for steady heating if the heating is highly concentrated low in the loop legs. Instead, cool condensations form and fall to the surface in a cyclical pattern that repeats on a time scale of hours. Resolvable condensations are indeed observed in active regions, but only in a small fraction of loops (Schrijver 2001). As a possible explanation for other EUV loops, Klimchuk & Karpen (2008) appeal to the multi-strand concept. The individual tiny condensations that occur within each strand will not be detected as long as the strands are out of phase. It is encouraging that the models predict excess densities similar to those of observed EUV loops. Mok *et al.* (2008) report thermal nonequilibrium behavior in their active region simulations. Hot loops form and cool, but without producing localized condensations.

We can summarize the state of understanding as follows. Much of the magnetically-closed corona is certainly *not* in static equilibrium, but much of it could be. A significant portion – perhaps the vast majority – is heated impulsively or is in thermal nonequilibrium, or some combination thereof. Most coronal heating mechanisms that have been proposed involve impulsive energy release (Klimchuk 2006; Uzdensky 2007; Cassak *et al.* 2008; Dahlburg *et al.* 2008; Rappazzo *et al.* 2008; Ugai 2008). It should be noted, however, that nanoflares that recur sufficiently frequently within the same flux strand (on a time scale much shorter than the cooling time) will produce quasi-static conditions. It is clear that more observational and theoretical work is required before the coronal heating problem will be solved.

5. **Coronal jets** (L. van Driel-Gesztelyi)

Coronal bright points are often observed to have jets – collimated transient ejections of hot plasma. *Hinode* (Kosugi *et al.* 2007) can now study the fine detail of jets which tend to occur preferentially inside coronal holes, which is consistent with reconnection taking place between the open magnetic field of the coronal hole and the closed loop field lines. Observations with the *Hinode*-XRT instrument (Golub *et al.* 2007) revealed that jets from polar coronal holes are more numerous than previously thought (60 jets day^{-1}, Savcheva *et al.* 2007; and even 10 jets hr^{-1}, Cirtain *et al.* 2007). The EIS instrument (Culhane *et al.* 2007a) allows direct measurement of the velocity of jets in the corona for the first time. The footpoints of the loops are seen to be red-shifted which is consistent with downflowing cooling plasma following reconnection. The (blue-shifted) jet is the dominant feature in velocity space but not in intensity (Kamio *et al.* 2007). Another new feature of jets is post-jet enhancement of cooler coronal lines observed by *Hinode*-EIS. This can be explained by the hot plasma in the jet not having sufficient velocity to leave the Sun and then falling back some minutes later (Culhane *et al.* 2007b).

Hinode-XRT observations of jets at the poles have shown mean velocities for jets of 160 km s^{-1} (Savcheva *et al.* 2007). Multiple velocity components were found in jets by Cirtain *et al.* (2007) in XRT polar coronal hole data: a spatio-temporal average of about 200 km s^{-1} as well as a much higher velocity measured at the beginning of each jet – with speeds reaching 800 km s^{-1}. Cirtain *et al.* (2007) interpret this early (and sometimes recurrent) fast flow as being due to plasma ejected at the Alfvén speed during the relaxation phase following magnetic reconnection. The mass flux supplied by about 10 jets per hour occurring in the two polar coronal holes was estimated to produce a net flux of 10^{12} protons m^{-2} s^{-1} which is only a factor of 10 less than the current estimates of the average solar wind flux. These small jets are providing a substantial amount of mass that is being carried into interplanetary space. A 3D numerical simulation has been carried out to compare with these observations (Moreno-Insertis *et al.* 2008) and is found to be consistent with several key observational aspects of polar jets such as their speeds and temperatures.

A study of the 3D morphology of jets became possible for the first time with stereoscopic observations by the *euvi*-SECCHI imagers (Howard *et al.* 2008) on board the twin *STEREO* spacecraft. The most important geometrical feature of the observed jets was found to be helical structures showing evidence of untwisting (Patsourakos *et al.* 2008). This is in agreement with the 3D model proposed by Pariat *et al.* (2008) with magnetic twist (untwisting) being the jet's driver.

6. **Flares** (L. Fletcher and J. Wang)

In this brief review we focus on progress in flare energy build-up and flare prediction, flare photospheric effects, high energy coronal sources, non-thermal particles, the flare-CME relationship, and recent advances with *Hinode*.

Where is the magnetic free energy stored in a flaring active region? Using the increasingly robust methods for extrapolating magnetic fields from vector magnetic field measurements, Schrijver *et al.* (2008) find evidence for pre-flare filamentary coronal currents located $< 20\,\mathrm{Mm}$ above the photosphere and Regnier & Priest (2007) show that in a newly-emerged active region the free energy is concentrated within the first 50 Mm (in an older, decaying region it resides at higher altitudes). Horizontal shear flows close to the neutral line prior to large flares (Deng *et al.* 2006) confirm the concentration of free energy in a small spatial scale, and Schrijver (2007) finds that if the unsigned flux within 15 Mm of the polarity inversion line exceeds 2×10^{21} Mx a major flare will occur within a day. Though Leka & Barnes (2007) find that the probability of flaring has only a weak relationship to the state of the photospheric magnetic field at any time, single or synthesized magnetic parameters are being used with some success to quantify flare probability and productivity. Georgoulis & Rust (2007) introduce the effective connected magnetic field of an active region, finding that this exceeds 1600 and 2100 G for M- and X-class flares, respectively, at 95% probability. LaBonte *et al.* (2007) surveyed the helicity injection prior to X-class flares producing a CME, finding occurrence only if the peak helicity flux exceeds 6×10^{36} Mx s^{-1}. Cui *et al.* (2007) find that flare probability increases with active region complexity, non-potentiality, and length of polarity inversion line. Impulsive phase HXR sources are concentrated where the magnetic field is strong, and where the reconnection rate is high (Temmer *et al.* 2007; Jing *et al.* 2008; Liu *et al.* 2008).

The last three years have seen effort directed towards understanding the magnetic and seismic effects of flares near the photosphere. It is clear that the photospheric magnetic field changes abruptly and non-reversibly during the flare impulsive phase (see e.g. Sudol & Harvey 2005 for a recent survey). Rapid changes in sunspot structure have also been detected by Chen *et al.* (2007) in 40% of X-class flares, 17% of M flares, and 10% C flares, while Wang (2006) finds variations in magnetic gradient close to the polarity inversion line consistent with a sudden release of magnetic shear. The obvious future task is to analyze vector magnetograms to identify changes in the 'twist' component of the field.

Flare-generated seismic waves, discovered by Kosovichev & Zharkova (1998) and amply confirmed in Cycle 23, also show the flare's photospheric impact. Donea *et al.* (2006), Kosovichev (2006, 2007) and Zharkova & Zharkov (2007) show that flare HXR sources and seismic sources correlate in space and time. Seismic sources are associated also with white light kernels, responsible for the majority of the flare radiated energy and strongly correlated with HXR sources (Fletcher *et al.* 2007) but the total acoustic energy is a small fraction of total flare energy (Donea *et al.* 2006). Nonetheless, looking at the cyclic variation of the total energy in the Sun's acoustic spectrum, Karoff & Kjeldsen (2008) propose that – analogous with earthquakes – flares may excite long-duration global oscillations.

The *RHESSI* mission has discovered several new types of flare coronal HXR sources, and we highlight here a hard-spectrum HXR source at least 150 Mm above the photosphere, with a nonthermal electron fraction of about 10% (Krucker *et al.* 2007b). Hard spectrum gamma-ray (200-800 keV) coronal sources have also been found, suggesting coronal electron trapping (Krucker *et al.* 2008). A soft-hard-soft spectral variation with time is present in some coronal sources as well as footpoints (Battaglia & Benz 2006), and this may be explicable by a combination of coronal trapping and stochastic electron acceleration (Grigis & Benz 2006). A curious observation with the Owens Valley Solar Telescope of terahertz emission may come from a compact coronal source of electrons at 800 keV, if the electrons are radiating in a volume with a magnetic flux density of 4.5 kG (Silva *et al.* 2007).

Discovering the origin and properties of the flare electron distribution continues to motivate advanced modeling and observations. Particle-in-cell simulations, used for some years in magnetospheric physics, have been harnessed to study acceleration in coronal magnetic islands produced by magnetic reconnection (Drake *et al.* 2006), and wave-particle distributions in current sheet and uniform magnetic field geometries (Karlicky & Barta 2007; Sakai *et al.* 2006). Flare Vlasov simulations are also being developed (e.g. Miteva *et al.* 2007; Lee *et al.* 2008). Detailed *RHESSI*-HXR spectroscopy has led to a new diagnostic for the flare electron angular distribution, based on photospheric HXR albedo (Kontar *et al.* 2006a). This diagnostic suggests that electron distributions might not be strongly downward-beamed in the chromosphere (Kontar *et al.* 2006b; Kasparova *et al.* 2007; though see Zharkova & Gordovskyy 2006 for an alternative explanation). Xu *et al.* (2008) studied *RHESSI* flares having an extended coronal source, finding evidence for an extended coronal accelerator. Looking at the larger coronal context, Temmer *et al.* (2008) show that peaks in the flare electron acceleration rate and in the CME acceleration rate are simultaneous within observational constraints ($\sim$ 5 minutes). *RHESSI* and *WIND* observations suggest that the spectral indices of flare and interplanetary electrons are correlated, but in a way that is inconsistent with existing models for flare X-ray emission, and the number of escaping electrons is only about 1/500th of the number of electrons required to produce the chromospheric HXR flux (Krucker *et al.* 2007a).

However, outstanding questions about the total electron number and supply in solar flares has prompted various authors to suggest alternatives to the 'monolithic' coronal electron beam picture. For example Dauphin (2007), Gontikakis *et al.* (2007) examine acceleration in multiple, distributed coronal region sites, while Fletcher & Hudson (2008) investigate the transport of flare energy to the chromosphere in the form of the Poynting flux of large-scale Alfvénic pulses, in strong and low-lying coronal magnetic fields.

The relationship between flares and CMEs continues to be an important topic. The general consensus regarding the spatial correspondence between CME position angle and flare location in the pre-*SOHO* era was that the flare is located anywhere under the span of the CME (e.g., Harrison 2006). However, using 496 flare-CME pairs in the SOHO era, Yashiro *et al.* (2008) found that the offset between the flare position and the central position angle (CPA) of the associated CME has a Gaussian distribution centered on zero, meaning the flare is typically located radially below the CME leading edge. This finding suggests a closer flare-CME relationship as implied by the CSHKP eruption model. Many flares are not associated with CMEs. Yashiro *et al.* (2006) studied two sets of flares one with and the other without CMEs. The number of flares as a function of peak X-ray flux, fluence, and duration in both sets followed a power law. Interestingly, the power law index was >2 for flares without CMEs, while <2 for flares with CMEs. In flares without CMEs, the released energy seems to go entirely into heating, which suggests that nanoflares may contribute significantly to coronal heating (see Section 4).

The launch of *Hinode* promises significant advances in flare physics in the next cycle. Thus far there have only been a small number of well-observed large flares, but observations of small flares start to show the combined power of *RHESSI* and *Hinode*. For example, Hannah *et al.* (2008) find a microflare not conforming to the usual relationship between flare thermal and nonthermal emission, and Milligan *et al.* (2008) show evidence for hot downflowing plasma in the flare corona, not explained in any existing flare model. Observational evidence for a new kind of reconnection, called slip-running reconnection, has been found by Aulanier *et al.* (2007), and sub-arcsecond structure in the white light flare sources has been demonstrated by Isobe *et al.* (2007). We look forward to the continued operation of these instruments, and the theoretical advances that they will bring, in the rise of Cycle 24.

7. **Coronal mass ejection initiation** (L. van Driel-Gesztelyi)

In recent years our physical understanding of CMEs has evolved from cartoons inspired by observations to full-scale numerical 3D MHD simulations constrained by observed magnetic fields. Notably, there has been progress made in simulating CME initiation by flux rope instabilities as inspired by observed filament motions during eruption which frequently include helical twisting and writhing (e.g. Rust & LaBonte 2005; Green *et al.* 2007). Several of these simulations use the analytical model of a solar active region by Titov & Démoulin (1999) as initial condition. The model contains a current-carrying twisted flux rope that is held in equilibrium by an overlying magnetic arcade. The two instabilities considered as eruption drivers are the ideal MHD helical kink and torus instabilities. The helical kink instability sets in if a certain threshold of (flux rope) twist (~ 2.5 turns for line-tied flux ropes) is reached (e.g., Török & Kliem 2005). Above this threshold, twist becomes converted into writhe during the eruption, deforming the flux rope (or filament) into a helical kink shape. On the other hand, a current-carrying ring (or flux rope) situated in an external poloidal magnetic field (B_{ex}) is unstable against radial expansion when the Lorentz self-force or hoop force decreases more slowly with increasing ring radius than the stabilizing Lorentz force due to B_{ex}. Known as the torus instability, its possible role in solar eruptions has been examined by Kliem & Török (2006) and Isenberg & Forbes (2007). In solar eruptions, the torus instability does not require a pre-eruptive, highly twisted flux rope, but (i) a sufficiently steep poloidal field decrease with height above the photosphere and (ii) an (approximately) semi-circular flux rope shape. Both the helical kink and torus instabilities may be responsible for initiating and driving prominence/filament eruptions and thus CMEs. The magnetic field decrease with height above the filament was shown to be critical whether a confined eruption or a full eruption occurs as well as for determining the acceleration profile, corresponding to fast CMEs for rapid (field) decrease, as it is typical of active regions, and to slow CMEs for gentle decrease, as is typical of the quiet Sun (Török & Kliem 2005, 2007; Liu 2008). The latter means that CMEs from complex active regions with steep field gradients in the corona are more likely to give rise to fast CMEs – something that is indeed observed.

More complex CME initiation models involve multiple magnetic flux systems, such as in the magnetic break-out model (e.g. Antiochos *et al.* 1999, DeVore & Antiochos 2008). In this model, magnetic reconnection removes unstressed magnetic flux that overlies the highly stressed core field and this way allows the core field to erupt. The magnetic break-out model involves specific nullpoints and separatrices. A multi-polar configuration was also included in the updated catastrophe model (Lin & van Ballegooijen 2005), the flux cancellation model (Amari *et al.* 2007), and the MHD instability models (Török & Kliem 2007). In an attempt to test CME initiation models with special attention to the breakout, Ugarte-Urra *et al.* (2007) analyzed the magnetic topology of the source regions of 26 CME events using potential field extrapolations and *TRACE*-EUV observations. They found only seven events which could be interpreted in terms of the breakout model, while a larger number of events (12) could not be interpreted in those terms. The interpretation of the rest remained uncertain. On the other hand, the CME event analyzed by Williams *et al.* (2005) provided a good example to indicate that also a combination of several mechanisms, e.g. magnetic break-out and kink instability, can be at work in initiating CMEs.

8. Global coronal waves and shocks (B. Vršnak)

The research on globally propagating coronal disturbances (large-amplitude waves, shocks, and wave-like disturbances) continued to be very dynamic. Maybe the most prominent characteristic of the past triennium was an enhanced effort to combine detailed multi-wavelength observations with the theoretical background. The empirical research resulted in a number of new findings, leading to new ideas and interpretations, whereas the theoretical research provided a better understanding of physical processes governing the formation and propagation of global coronal disturbances.

For the first time the EUV signatures of a global coronal wave ('EIT waves') were measured at high cadence by *STEREO*-EUVI, related to the eruption of 2007 May 19 (Long *et al.* 2008; Veronig *et al.* 2008). Long *et al.* (2008) reported for the first time the wave signatures at 304 Å. Furthermore, they confirmed the idea by Warmuth *et al.* (2001) that velocities of EIT waves measured by *SOHO*-EIT are probably significantly underestimated due to the low cadence of the EIT instrument. Veronig *et al.* (2008) revealed reflection of the wavefront from the coronal hole boundary, indicating that the observed disturbance represents a freely-propagating MHD wave.

The data from pre-*STEREO* instruments continued to be exploited fruitfully. Mancuso & Avetta (2008) analyzed the UV-spectrum (*SOHO*-UVCS) of the 2002 July 23 coronal shock, and concluded that the plasma-to-magnetic pressure ratio β could be an important parameter in determining the effect of ion heating at collisionless shocks. Employing the extensive data on CMEs, solar energetic particle (SEP) events, and type II radio bursts during the *SOHO* era, Gopalswamy *et al.* (2008b) demonstrated that essentially all type II bursts in the decameter-hectometric (DH) wavelength range are associated with SEP events once the source location is taken into account. Shen *et al.* (2007) proposed a method to determine the shock Mach number by employing the CME kinematics, type II burst dynamic spectrum, and the extrapolated magnetic field. Analyzing one Moreton wave that spanned over almost 360°, Muhr *et al.* (2008) revealed two separate radiant points at opposite ends of the two-ribbon flare, indicating that the wave was driven by the CME expanding flanks. Veronig *et al.* (2006) found out that the Moreton/EIT wave segments where the front orientation is normal to the coronal hole boundary can intrude into the coronal hole up to 60–100 Mm.

Regarding the nature of global coronal disturbances, some new ideas appeared. For example, Attrill *et al.* (2007) attributed EIT waves to successive reconnections of CME flanks with coronal loops, which could explain the association of EIT 'waves' and shallow coronal dimmings which are formed behind the bright front. Wills-Davey *et al.* (2007) proposed that slow EIT waves are caused by MHD slow-mode soliton-like waves. Delannee *et al.* (2008) performed a 3D MHD simulation to show that EIT 'waves' could be a signature of a current shell formed around the erupting structure. Balasubramaniam *et al.* (2007) demonstrated that the visibility of Moreton waves increases when sweeping over filaments and filament channels, so they put forward the idea that a significant contribution to the Moreton-wave H_α signature might be coming from coronal material of enhanced density.

The question of the origin of coronal shocks and large amplitude waves continues to be one of the central topics in this field. The published studies showed a variety of results, some biased towards the CME-driven option, some favoring the flare-ignited scenario, and some finding arguments for small scale ejecta (e.g., Chen 2006; Pohjolainen & Lehtinen 2006; Shanmugaraju *et al.* 2006a,b; Subramanian & Ebenezer 2006; Cho *et al.*, 2007; Liu *et al.* 2007; Reiner *et al.* 2007; White 2007; Grechnev *et al.* 2008; Muhr *et al.* 2008; Veronig *et al.* 2008; Magdalenic *et al.* 2008; Mancuso & Avetta 2008; Pohjolainen 2008). To illustrate the current level of ambiguity in such studies, let us mention that for one well observed event two sets of authors came to diametrally opposite conclusions: Vršnak *et al.* (2006) favored a flare driver, whereas Dauphin *et al.* (2006) advocate a CME. The status of the 'CME/flare controversy' was reviewed recently by Vršnak & Cliver (2008).

Related to the formation and propagation of large-amplitude waves and shocks, a number of important theoretical papers were published. Pagano *et al.* (2007) investigated the role of magnetic fields and showed that a CME-driven wave propagates to longer distances in the absence of magnetic field than in the presence a weak open field. Ofman (2007) modeled the wave activity following a flare by launching a velocity pulse into a model active region and demonstrated that the resulting global oscillations are in good agreement with observations. Employing the photospheric magnetic field measurements, Liu *et al.* (2008) performed a 3D MHD simulation of a CME, and showed that the shock segment at the nose of the CME remains quasi-parallel most of the time. In the simulation of reconnection in a vertical current sheet, Barta *et al.* (2007) revealed the formation of large-amplitude waves associated with changes of the reconnection rate, which might explain flare-associated type II bursts in the wake of CMEs. Zic *et al.* (2008) developed an analytical MHD model describing the formation of large-amplitude waves by impulsively expanding 3D pistons. The model provides an estimate of the time/distance at which the shock should be formed, dependent on the source-surface acceleration, the terminal velocity, the initial source size, the ambient Alfvén speed, and plasma β.

Finally, it should be noted that a comprehensive review on coronal waves and shocks was published by Warmuth (2007). Gopalswamy (2006e) reviewed the relationship between CMEs and type II bursts, while Mann & Vršnak (2007) surveyed the relationship between CMEs, flares, coronal shocks, and particle acceleration.

9. **Coronal dimming** (R. Harrison and L. van Driel-Gesztelyi)

There is no strict definition of the phenomenon which we call coronal dimming. Most authors consider coronal dimming to be a depletion of extreme-UV (EUV) or X-ray emission from a large region of the corona, which is thought to be closely associated with coronal mass ejection (CME) activity. Clearly, understanding the onset phase of a CME is one of the key issues in solar physics today, so the study of such dimming activity could well be of critical importance. However, most of the literature deals with dimming in a rather hand-waving manner, with the emphasis on phenomenological studies and associations, no strict definitions of what constitutes a dimming event (e.g., the depth of the depletion in intensity, the size of the dimming region, etc.) and little in terms of a physical interpretation of the plasma characteristics of the dimming region. Having said that, some key studies are emerging which do tackle such issues head on, and with the advent of the new STEREO and Hinode spacecraft, along with the on-going SOHO and TRACE missions, as well as the up-coming SDO mission, we have many tools to address this area of research effectively.

Coronal dimming is not a newly discovered phenomenon; Rust and Hildner (1976) reported such an event using *Skylab* observations. More recently, from the late 1990s, dimming was reported using X-ray and EUV, imaging and spectroscopic data, from the *SOHO* and *Yohkoh* spacecraft (e.g. Sterling & Hudson 1997; Harrison 1997; Gopalswamy & Hanaoka 1998; Zarro *et al.* 1999; Harrison & Lyons 2000), and dimming has taken center-stage in the study of mass ejection onset in recent years (e.g., recent studies include Moore & Sterling 2007; Zhang *et al.* 2007; Reinard & Biesecker 2008). In many ways coronal dimming has become a well established phenomenon.

The majority of dimming reports involve EUV or X-ray imaging, and we have excellent tools aboard *SOHO*, *TRACE*, *STEREO* and *Hinode* to identify and study the topology and evolution of dimming regions. On the other hand, there are spectroscopic studies of dimming which are providing key plasma information, despite having limited fields of view or cadence. The combination of imaging and spectroscopy is essential, but it is worth stressing some of the spectroscopic studies because they stress the physical processes which are involved in the dimming and, perhaps, the CME onset process.

EUV spectroscopy has been used to confirm that the dimming process represents a loss of mass – i.e., it is a density depletion – rather than a change in temperature (Harrison & Lyons 2000; Harrison *et al.* 2003). Indeed, these studies have demonstrated the loss of between 4.3×10^{10} and 2.7×10^{14} kg, in each case consistent with the mass of an overlying, associated CME. If we are identifying the plasma which becomes (part of) the CME, then this is an exciting phenomenon; studies focusing on the properties of the dimming plasma, before, during and after the event, will be essential for understanding the CME onset (Harrison & Bewsher 2007).

Hudson *et al.* (1996) showed that the timescale of the dimming formation observed in *Yohkoh*-Soft X-ray Telescope (SXT; Tsuneta *et al.* 1991) data is much faster than corresponding conductive and radiative cooling times. More recently, data obtained by the *Hinode*-Extreme ultra-violet Imaging Spectrometer (EIS; Culhane *et al.* 2007) have shown detection of Doppler blue-shifted plasma outflows of velocity ≈ 40 km s^{-1} corresponding to a coronal dimming (Harra *et al.* 2007). This result confirms a similar finding (Harra & Sterling 2001) obtained with the *SOHO*/Coronal Diagnostic Spectrometer (CDS; Harrison *et al.* 1995). In addition, *SOHO*-CDS limb observations have been used to show the formation of a dimming region through the outward expansion of pre-CME EUV loops (Harrison & Bewsher, 2007), which is consistent with such blueshifts. Imada *et al.* (2007) find that *Hinode*-EIS data of a dimming shows a dependence of the outflow velocity on temperature, with hotter lines showing a stronger plasma outflow (up to almost $150\,\mathrm{km\,s^{-1}}$. These works collectively support the primary interpretation of coronal dimmings as being due to plasma evacuation.

Statistical studies are becoming important in truly establishing the relationship with CMEs. Reinard & Biesecker (2008) have recently studied the properties of 96 dimming events, using EUV imaging, associated with CME activity. They confirmed earlier studies which showed that the dimming events could be long-lasting, ranging from 1 to 19 hours, and compared the size of the dimming regions to the associated CMEs. They also tracked the number of dimming pixels through each event and showed that the 'recovery' after the dimming often took the form of a two-part slope (plotted as dimming area vs. time).

Bewsher *et al.* (2008) have produced the first statistical and probability study of the dimming phenomenon using spectroscopy. They recognized that while we have associated CMEs and dimming, there has not been a thorough statistical study which can really identify the degree of that association, i.e., to put that relationship on a firm footing. Using spectroscopy, they also recognized the importance of studying this effect for different temperatures. They made use of over 200 runs of a specific campaign using the SOHO spacecraft with an automated procedure for identifying dimming.

Key results included the following: Up to 84% of the CMEs in the data period can be back-projected to dimming events – and this appears to confirm the association that we have been proposing. However, they also showed, as did other spectral studies, that the degree of dimming varies between temperatures from event to event. If different dimming events have different effects at different temperatures then this is a problem for monitoring such events with fixed-wavelength imagers.

Assuming that magnetic field lines of the CME are mostly rooted in the dimmings, several properties derived from the study of dimmings can be used to obtain information about the associated CME. Firstly, calculations of the emission measure and estimates of the volume of dimmings can give a proxy for the amount of plasma making up the CME mass (Sterling & Hudson 1997; Harrison & Lyons 2000; Harrison *et al.* 2003; Zhukov & Auchère 2004). Secondly, the spatial extent of coronal dimmings can give information regarding the angular extent of the associated CME (Thompson *et al.* 2000; Harrison *et al.* 2003; Attrill *et al.* 2007, van Driel-Gesztelyi *et al.* 2008). Thirdly, quantitative measurement of the magnetic flux through dimmings can be compared to the magnetic flux of modeled magnetic clouds (MC) at 1 AU (Webb *et al.* 2000; Mandrini *et al.* 2005; Attrill *et al.* 2006; Qiu *et al.* 2007), see Démoulin (2008) for a review. Fourth, studying the evolution of the dimmings, particularly during their recovery phase can give information about the evolution of the CME post-eruption (Attrill *et al.* 2006; Crooker & Webb 2006) providing proof for e.g. magnetic interaction between the expanding CME and open field lines of a neighboring coronal hole. Finally, study of the distribution of the dimmings, their order of formation and measurement of their magnetic flux contribution to the associated CME enabled Mandrini *et al.* (2007) to derive an understanding of the CME interaction with its surroundings in the low corona for the case of the complex 28 October 2003 event. They, building on the model proposed by Attrill *et al.* (2007), demonstrated that magnetic reconnection between field lines of the expanding CME with surrounding magnetic structures ranging from small- to large-scale (magnetic carpet, filament channel, active region) make some of the field lines of the CME 'step out' from the flaring source region. Magnetic reconnection is driven by the expansion of the CME core resulting from an over-pressure relative to the pressure in the CME's surroundings. This implies that the extent of the lower coronal signatures match the final angular width of the CME. Through this process, structures over a large-scale magnetic area become CME constituents (for a review see van Driel-Gesztelyi *et al.* 2008). From the wide-spread coronal dimming some additional mass is supplied to the CME.

Observations show that coronal dimmings recover whilst suprathermal uni- or bi-directional electron heat fluxes are still observed at 1 AU in the related ICME, indicating magnetic connection to the Sun. The questions why and how coronal dimmings disappear whilst the magnetic connectivity is maintained was investigated by Attrill *et al.* (2008) through the analysis of three CME-related dimming events. They demonstrated that dimmings observed in *SOHO*-EIT data recover not only by shrinking of their outer boundaries but also by internal brightenings. They show that the model developed in Fisk & Schwadron (2001) of interchange reconnections between 'open' magnetic field and small coronal loops is applicable to observations of dimming recovery. Attrill *et al.* (2008) demonstrate that this process disperses the concentration of 'open' magnetic field (forming the dimming) out into the surrounding quiet Sun, thus recovering the intensity of the dimmings whilst still maintaining the magnetic connectivity of the ejecta to the Sun.

Although this brief summary cannot report on all studies, it is clear that we have made progress very recently in putting the dimming phenomenon on a firm footing – the association is real – and we are making in-roads into studies of the plasma activities leading to the dimming/CME onset process. With the continuation of the *SOHO* mission, as well as *TRACE*, combined with the new *STEREO* and *Hinode* missions and the upcoming *SDO* mission, this is a topic which will receive much attention in the next few years.

10. The link between low-coronal CME signatures and magnetic clouds (C. Mandrini)

A major step to understanding the variability of the space environment is to link the sources of coronal mass ejections (CMEs) to their interplanetary counterparts, mainly magnetic clouds (MCs), a subset of interplanetary CMEs characterized by enhanced magnetic field strength when compared to ambient values, a coherent and large rotation of the magnetic field vector, and low proton temperature (Burlaga 1995). Identifying the solar sources and comparing qualitatively and quantitatively global characteristics and physical parameters both in the Sun and the interplanetary medium provide useful tools to constrain models in both environments.

Under the assumption that dimmings (see Section 9) at the Sun mark the position of ejected flux rope footpoints (Webb *et al.* 2000), the magnetic flux through these regions can be used as a proxy for the magnetic flux involved in the ejection and, thus, be compared to the magnetic flux in the associated interplanetary MC. Another proxy for the flux involved in an ejection is the reconnected magnetic flux swept by flare ribbons, as they separate during the evolution of two-ribbon flares. Using EUV dimmings as proxies and reconstructing the MC structure from one spacecraft observations, Mandrini *et al.* (2005) and Attrill *et al.* (2006) found that the magnetic flux in dimming regions was comparable to the azimuthal MC flux, while the axial MC flux was several times lower. Qui *et al.* (2007) analyzed and compared the reconnected magnetic flux to the total MC flux, finding similar results (see also Yurchyshyn *et al.* 2006; Longcope *et al.* 2007; Möstl *et al.* 2008, where MC data from two spacecraft were used).

These results led to the conclusion that the ejected flux rope is formed by successive reconnections in a sheared arcade during the eruption process, as opposed to the classical view of a previously existing flux rope being ejected. However, in extreme events that occur in not isolated magnetic configurations, it was found that the flux in dimmings did not agree with the MC flux (Mandrini *et al.* 2007). This mismatch led these authors to propose a scenario in which dimmings spread out to large distances from the initial erupting region through a stepping reconnection process (in a similar process to that proposed by Attrill *et al.*, 2007, for the interpretation of EIT waves). An overview of earlier works on quantitative comparisons of solar and interplanetary global magnetohydrodynamic invariants, such as magnetic flux and helicity, can be found in Démoulin (2008).

Qualitative comparisons are also useful tools to understand the eruption process. Studying the temporal and spatial evolution of EUV dimmings, together with soft X-ray coronal observations, in conjunction with interplanetary *in situ* data of suprathermal electron fluxes, Attrill *et al.* (2006) and Crooker & Webb (2006) derive an eruption scenario in which interchange magnetic reconnection between the expanding CME loops and the open field lines of a polar coronal hole led to the opening of one leg of the erupting flux rope. Harra *et al.* (2007), combining EUV and H_α solar observations of eruptive events with *in situ* magnetic field and suprathermal electron data, were able to understand the sequence of events that produced two MCs with opposite magnetic field orientations from the same magnetic field configuration.

The simple comparison of the magnetic field orientation in the erupting configurations, which can be inferred from magnetograms, the directions of filaments, coronal arcades or loops, with the axis of the associated MCs, can give clues about the mechanism at the origin of solar eruptions. Green *et al.* (2007) analyzed in detail associations of filament eruptions and corresponding MCs, and they found that when the filament and MC axis differed by a large angle, the direction of rotation was related to the magnetic helicity sign of the erupting configuration (see also Harra *et al.* 2007). The rotation was consistent with the conversion of twist into writhe, under the ideal MHD constraint of helicity conservation, providing support for the assumption of a flux rope topology where the kink instability sets in during the eruption (see the review by Gibson *et al.* 2006).

11. Coronal mass ejections in the heliosphere (R. Harrison)

In the 1970s the *Helios* spacecraft operated from solar orbits with perihelion 0.31 AU. Zodiacal light photometers were used to detect CMEs in the inner heliosphere (see, e.g., Richter *et al.* 1982; Jackson & Leinert 1985). CME images were constructed from three photometers which scanned the sky using the spacecraft rotation. More recently, a major advance was made with the launch, in 2003, of the Solar Mass Ejection Imager (SMEI) aboard the *Coriolis* spacecraft (Eyles *et al.* 2003). This instrument maps the entire sky with three cameras each scanning 60^o slices of the sky as the spacecraft moves around the Earth, and thus, it has pioneered full-sky mapping aimed specifically at the detection of CMEs propagating through the inner heliosphere (see e.g. recent papers by Kahler & Webb 2007 and Jackson *et al.* 2007).

The combination of wide-angle heliospheric mapping from out of the Sun-Earth line is now being satisfied by the Heliospheric Imagers (HI) (Harrison *et al.* 2008) aboard the NASA *STEREO* spacecraft. The development of these instruments has come very much from the SMEI heritage and, with the unique opportunities from the STEREO spacecraft locations, these instruments are able to image those CME events directed towards the Earth. Indeed, for the first time, the HI instruments provide a view of the passage of CMEs along virtually the entire Sun-Earth line and such observations represent a major milestone in investigations of the influence of solar activity on the Earth and human systems.

Each HI instrument consists of two wide-angle telescopes mounted within a baffle system enabling imaging of the heliosphere from the corona out to Earth-like distances and beyond. The low scattered light levels and sensitivity allow the detection of stars down to magnitudes of 12–13. This performance is excellent for the detection of solar ejecta and solar wind structure through the detection of Thomson scattered photospheric light off free electrons in regions of density enhancement.

The *STEREO* spacecraft were launched in October 2006 with full scientific operation of the HI instruments starting from April 2007. The spacecraft are in near Earth-like solar orbits, with one ahead and one behind the Earth in its orbit. They are drifting away at 22.5° per year (Earth-Sun-spacecraft angle). The spacecraft are labelled *STEREO A* and *STEREO B*, for ahead and behind.

The first HI observations of CMEs in the heliosphere, tracked out to Earth-like distances, were reported by Harrison *et al.* (2008). The same instruments are also reaping the benefits of wide-angle imaging of the heliosphere with observations of comets (Fulle *et al.* 2007; Vourlidas *et al.* 2007), even the imaging of co-rotating interaction regions (Sheeley *et al.* 2008a,b; Rouillard *et al.* 2008a) and impacts of CMEs at other planets (Rouillard *et al.* 2008b).

With the HI instruments we now have a real opportunity to begin to relate the coronal events that we call CMEs with their heliospheric counterparts, commonly referred to as ICMEs – Interplanetary CMEs. Most ICME studies have been performed utilizing *in situ* particle and field observations, and it is clear that heliospheric imaging can provide a thorough test of the interpretation of such *in situ* data on the topology and propagation of CMEs in the heliosphere. Indeed, the uniqueness of this opportunity is well illustrated by the fact that there are a number of extremely basic observational tests which can be made with the new facility to underline our current understanding of how CMEs travel out through the Solar System.

Crooker & Horbury (2006) have recently reviewed the propagation of ICMEs in the heliosphere, utilizing *in situ* data. They note that cartoon sketches of ICMEs commonly show magnetic field lines connected to the Sun at both ends. Furthermore, reporting on the work of Gosling *et al.* (1987), Crooker *et al.* (2002), and others, they note that it is widely accepted that counter-streaming particle beams in ICMEs are a sign that both ends of the ICME are indeed connected to the Sun. This is known as a ‘closed’ ICME. On the other hand, uni-directional beams may signal connection at only one end – an ‘open’ ICME. Logically, then, the lack of beams would appear to signal disconnection at both ends. In this case the ICME has become an isolated plasmoid.

Given this interpretation, *in situ* observations of ICMEs appear to show many events which are apparently connected to the Sun at both footpoints, and rather fewer events which appear to be connected at one end. Complete disconnection of an ICME (a plasmoid) appears to be rare. In addition, the *in situ* observations suggest that CMEs are connected to the Sun over extremely long distances; Riley *et al.* (2004) looked for the degree of ‘openness’ of ICMEs using observations of counter-streaming electrons from Ulysses data and could detect no trend in the openness of ICMEs with distance out to Jupiter. If ICME connectivity to the Sun is the same at 1 AU as it is at 5 AU then it can be argued that an ascending CME could still be rooted at the Sun for a week, or, indeed, much longer.

In reality, an ascending flux rope would most likely contain a mix of open and closed field lines, driven by apparently random reconnection events (Crooker & Horbury 2006; Gosling *et al.* 1995). Complete disconnection of the structure appears to be unlikely.

With the new *STEREO*-HI data we should be able to test this scenario, and this has been reported by Harrison *et al.* (2008). The HI data appear to confirm the *in situ* interpretation showing coherent structures, apparently still connected to the Sun over long distances. There is no evidence for events pinching-off. However, this in turn presents us with an anomaly. McComas (1995) has argued that the heliospheric magnetic flux does not continually build up, so flux must be shed through reconnection somehow during the ICME process. If we are rejecting the plasmoid or disconnected ICME scenario then we must find another way of limiting the flux build up over time.

In the absence of evidence for the pinching-off of CMEs, an interchange reconnection process has been suggested as the mechanism by which CMEs disconnect from the Sun (Gosling *et al.* 1995; Crooker *et al.* 2002). The basic idea is that the ascending CME can travel a considerable distance, well beyond the Earth, still connected to the Sun, and that perhaps days or even weeks after the onset, the legs of the CME, still rooted in the Sun, will interact with adjacent open field lines at low altitude in the corona; reconnection results in the formation of low-lying loops as one CME leg reconnects with the adjacent fields and an outward ascending kink-shaped structure ascends into the heliosphere from the site of one of the original CME footpoints.

This approach has a few attractive points. For example, it seems logical that the site of the greatest field density, magnetic complexity and field-line motion would be the most likely site of any reconnection in the ascending CME. However, assuming that such interchange reconnection is the ‘end game’ of a CME, and that this low level reconnection results in the outward propagation of a kinked field-line configuration, what might we expect to observe and, indeed, have we seen such features? Harrison *et al.* (2008) indeed point to observations of narrow V-shaped structures identified in the HI data that could be candidates for such reconnection events.

It is early days for this work using *STEREO* but the indications are that there is plenty to be gained from these studies. As the mission progresses we anticipate more opportunities where we have the chance to combine both imaging and *in situ* measurements of specific events, and their impacts, as well as to model CMEs in the heliosphere in 3D as never before. Thus, this report should be take as an early statement on the progress and direction of this work which is opening a new chapter in solar, heliospheric and space weather physics.

12. Coronal mass ejections and space weather (N. Gopalswamy)

CMEs cause adverse space weather in two ways: (*i*) when they arrive at Earth’s magnetosphere, they can couple to Earth’s magnetic field and cause major geomagnetic storms (Gosling *et al.* 1990); and (*ii*) they can drive fast mode MHD shocks that accelerate solar energetic particles (Reames 1999). Significant progress has been made on both these aspects over the past few years. In the case of geomagnetic storms, connecting the magnetic structure and kinematics of ICMEs observed at 1 AU to the CME source region at the Sun has received considerable attention. In the case of SEPs, assessing the contribution from flare reconnection and shock to the observed SEP intensity has been the focus. The importance of the variability in the Alfvén speed profiles in the outer corona is also under investigation because of its importance in deciding the shock formation.

12.1. *Geomagnetic storms*

High-Speed Solar Wind Streams (HSS) interacting with the slow solar wind result in corotating interaction regions (CIRs), which also can produce geomagnetic storms (Vršnak *et al.* 2007a), but they are generally weaker than the CME-produced storms (Zhang *et al.* 2007). Occasionally, the CIR and ICME structures combine to produce major storms (Dal Lago *et al.* 2006). Multiple CMEs are often involved producing some super-intense storms (Gopalswamy *et al.* 2007; Zhang *et al.* 2007). There are numerous effects produced by the

ICMEs in the magnetosphere and various other layers down to the ground (see Borovsky *et al.* 2006; Kataoka & Pulkkinen 2008).

The key element of ICMEs for the production of geomagnetic storms is the southward magnetic field component. While the quite heliospheric field has no out of the ecliptic field component (except for Alfvenic fluctuations in the solar wind), a CME adds this component to the interplanetary (IP) magnetic field. If an ICME has a flux rope structure, one can easily see that the azimuthal component of the flux-rope field or its axial component forms the out of the ecliptic component. In ICMEs with a flux rope structure (i.e., magnetic clouds), it is easy to locate the southward component from the structure of the cloud (Gopalswamy 2006a; Wang *et al.* 2007; Gopalswamy *et al.* 2008a). In non-cloud ICMEs, it is not easy to infer the location of the southward component. If the ICMEs are shock-driving, then the magnetosheath between the shock and the driving ICME (Kaymaz & Siscoe 2006; Lepping *et al.* 2008) can contain southward field and hence cause geomagnetic storms (Gopalswamy *et al.* 2008a). The cloud and sheath storms can be substantially different (Pulkkinen *et al.* 2007).

Once an IP structure has a southward magnetic field, the efficiency with which it causes geomagnetic storm depends on the strength of the magnetic field and the speed with which it hits the magnetosphere (Gonzalez *et al.* 2007; Gopalswamy 2008d). Statistical investigations have shown that the storm intensity (measured e.g., by the Dst index) is best correlated with the speed-magnetic field product in magnetic clouds and their sheaths. Interestingly, an equally good correlation is obtained when the magnetic cloud/sheath speed is replaced by the CME speed measured near the Sun (Gopalswamy *et al.* 2008a). This suggests that if one can estimate the magnetic field in CMEs near the Sun, the strength of the ensuing magnetic storm can be predicted. The ICME speed can be predicted based on the CME speed by quantifying the interaction between CMEs and the solar wind (Xie *et al.* 2006; Nakagawa *et al.* 2006; Jones *et al.* 2007; Vršnak & Zic, 2007). Most of the storm-causing CMEs are halo CMEs, which are subject to projection effects and hence space speeds cannot be easily measured (Kim *et al.* 2007; Gopalswamy & Xie 2008; Howard *et al.* 2007; Vršnak *et al.* 2007b). There have been several attempts to use the sky-plane speed of CMEs to obtain their space speed (Xie *et al.* 2006; Michalek *et al.* 2008; Zhao 2008) with varying extents of success. The magnetic field strength and kinetic energy of CMEs are somehow related to the free energy available in the source region. Quantifying this free energy has been a difficult task (Ugarte-Urra *et al.* 2007; Schrijver *et al.* 2008).

The solar sources of CMEs need to be close to the disk center for the CMEs to make a direct impact on Earth and they have to be fast. In fact the solar sources of magnetic clouds, storm-causing CMEs, and halo CMEs have been shown to follow the butterfly diagram suggesting that only sunspot regions have the ability to produce such energetic CMEs (Gopalswamy 2008d). The average near-Sun speed of CMEs that cause intense geomagnetic storms is $\sim 1000\,\mathrm{km\,s^{-1}}$ (Gopalswamy 2006b; Zhang *et al.* 2007), similar to the average speed of halo CMEs (Gopalswamy *et al.* 2007) because many of the storm-producing CMEs are halo CMEs. Halo CMEs are more energetic (Lara *et al.* 2006; Liu 2007; Gopalswamy *et al.* 2007, 2008a) and end up being magnetic clouds at 1 AU. Most halo CMEs ($\sim 70\%$) are geoeffective. Non-geoeffective halos are generally slower, originate far from the disk center, and originate predominantly in the eastern hemisphere of the Sun. The geoeffectiveness rate of halo CMEs has been reported to be anywhere from $\sim 40\%$ to more than 80% (Yemolaev & Yermolaev 2006), but the difference seems to be due to different definitions used for halo CMEs (some authors have included all CMEs with width $> 120^{\circ}$ as halos) and the sample size (Gopalswamy *et al.* 2007). The geoeffectiveness rate of CMEs may be related to the fact that more ICMEs are observed as magnetic clouds during solar minimum than during solar maximum (Riley *et al.* 2006). It is possible that all ICMEs are magnetic clouds if viewed appropriately (Krall 2007). This suggestion is consistent with the ubiquitous nature of post eruption arcades, which seem to indicate flux rope formation in the eruption process (Kang *et al.* 2006; Qiu *et al.* 2007; Yurchyshyn 2008). While the reconnection process certainly forms a flux rope, it is not clear if the reconnection creates a new flux rope or fattens an existing one.

12.2. *SEP events*

Energetic storm particle (ESP) events are the strongest evidence for SEP acceleration by shocks, but this happens when the shocks arrive at the observing spacecraft near Earth (Cohen *et al.* 2006). This means the shocks must have been stronger near the Sun accelerating particles to much higher energies. The strongest evidence for SEPs in flares is the gamma-ray lines, which are now imaged by RHESSI (Lin 2007). All shock-producing CMEs are associated with major flares (M- or X-class in soft X-rays), so both mechanisms must operate in most SEP events. There has been an ongoing debate as to which process is dominant based on SEP properties such as the spectral and compositional variability at high energies (Tylka & Lee 2006; Cane *et al.* 2007).

The easiest way to identify shocks near the Sun are the type II radio bursts especially at frequencies below 14 MHz, which correspond to the near-Sun IP medium (Gopalswamy 2006c). Analyzing electrons and protons in SEP events, Cliver & Ling (2007) have found evidence for a dominant shock process including flatter SEP spectra, apparent widespread sources, and high association with long wavelength type II bursts. A recent statistical study finds the SEP association rate of CME steadily increases with CME speed and width especially and there is one-to-one correspondence between SEP events and CMEs from the western hemisphere with long wavelength type II bursts (Gopalswamy *et al.* 2008b). Type II burst studies have also have concluded that the variability in Alfvén speed in the outer corona decides the formation and strength of shocks (Shen *et al.* 2007; Gopalswamy *et al.* 2008c). For example, a 400 km s^{-1} CME can drive a shock, while a 1000 km s^{-1} CME may not drive a shock, depending on the local Alfvén speed.

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