DIVISION II - SUN & HELIOSPHERE

10 Solar activity
12 Solar radiation & structure
49 The interplanetary plasma & the heliosphere

REPORTS ON ASTRONOMY 1996
from IAU Commissions 10, 12 and 49

Oddbjørn Engvold; President IAU Commission 10
Franz-Ludwig Deubner; President IAU Commission 12
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i. COMMENTS BY THE COMMISSIONS PRESIDENTS

The time period covered by this report (1 July 1993 - 30 June 1996) has seen the flawless launch and operation of SOHO, the full development of the Global Oscillation Network (GONG) and other seismology networks, a continued successful operation of YOHKOH, the southern and northern passages of ULYSSES, as well as significant advances in high resolution solar observing techniques.

The topics of the present report have been chosen with the aim to maintain a long-term balance in the coverage of activities of the three Commissions, ranging from instrumentation and observing techniques to the most important work and new scientific results from studies of the Sun and Heliosphere. It is our intention to provide critical reviews of the field, which may also be useful for the non-specialist reader.

Helioseismology is still a vigorously expanding subject, with several well attended international meetings and workshops each year; it has also made numerous proselytes from the night side of the Earth, working on Asteroseismology. Diffraction limited resolution is now almost achieved with ground-based solar observations in the visible and near IR, using modern techniques of image restoration. Studies of processes on the Sun in the realm of small spatial scales (down to $\frac{1}{4}$ arcsecond, or less) now represent real possibilities. Also, invaluable multi-λ coverage in solar observations, through coordinated combinations of solar instruments,- space- and ground-based, has been inspired and made possible by worldwide access to modern communication network.

The format of this report also reflects the consolidation of our three Commissions into IAU Division II "The Sun and the Heliosphere", which was implemented at the XXIInd General Assembly of the IAU in The Hague, The Netherlands, August 1994. The increased interdiciplinary contacts and cooperations between the Commissions that have taken place under this new structure, have been most helpful. It is our opinion that the new structure is mutually beneficial and may serve to strengthen and further the science of our fields. Its detailed form may be improved and shaped in the next triennia ahead.

As Commission Presidents we like to thank the members of the Organizing Committees and Commission members who have helped in dealing with various issues and challenges during the past triennium. Last but not least, we are most grateful to the authors of the various reviews for their valuable contributions.

I. Appenzeller (ed.), Reports on Astronomy, Vol. XXIIIA, 119.

Reports from IAU Commission 10

1. PROGRESS IN SOLAR INSTRUMENTATION

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1.1. INTRODUCTION

Improvements of resolution in time, space and wavelength are crucial in modern solar instrumentation. The extension of data sets in time, space and wavelength, is also required in studies of time-dependent events connecting distant regions of the Sun. Many instruments now fulfill both kinds of requirements. In addition to a generally large volume of data, the accuracy of measurements is obviously important, in particular in the case of polarization analysis.

Among the new advances in solar observations, it is noted that use of many ground-based telescopes and space probes are often coordinated in the framework of observing campaigns. Moreover, the development of data bases is very promising, and there is good hope that, very soon, solar data of interest to a broader community will be easily accessible.

The space is too limited to allow for an exhaustive review. Further information can be found in recent reviews about solar instrumentation by Antonucci (1966) and Mein (1966).

1.2. SOLAR INTERIOR

The present review will only deal with optical instruments, excluding such as neutrino detection. Helioseismology includes two kinds of observations: (1) integrated velocity oscillations and (2) systematic recordings of solar images. From the ground, such studies require long time series to improve the accuracy of frequency measurements. The gaps in time series are avoided by involving an increasing number of observing stations (there is 6 for IRIS and BISON) (Lazrek 1966). In the case of imaging instruments, spatial resolutions are improved ($\sim 1"$ for TON and GONG). Since the successful launch of SOHO, the access to GOLF, VIRGO and MDI/SOI provides unique data for helioseismology. Extended reviews on these instruments have been presented earlier (Fleck et al. 1995).

The measurements of the solar diameter take advantage of two new astrolabes, at Santiago and San Fernando, in addition to existing facilities such as the Calern instrument.

1.3. PHOTOSPHERE AND CHROMOSPHERE

The main advances in optical observations concern high angular resolution, multi-line and 2-D spectroscopy, and spectro-polarimetry.

The techniques for high angular resolution are discussed by Dr. C.U. Keller in his review for IAU Commission 12.

While multi-line spectroscopy is developed in existing spectrographs, mainly for flare observations (Ondrejov, Nanjing, Kiev), 2-D spectroscopy is becoming more commonly used. Narrow-band filters consist of UBF and Fabry-Perot devices, or of two Fabry-Perot systems, as in filter of the German VTT telescope at Tenerife (Bendlin and Folkmer 1995). Multi-line imaging spectroscopy is performed by the MSDP spectrograph of the same instrument. Generally, the use of CCD cameras has become most effective.

Substantial advance has been made in spectro-polarimetry using slit spectrographs. The ASP uses a two-beams optical system and leads to very accurate polarization measurements Lites et al. (1995). Fast polarization modulators are applied for the ZIMPOL II system (Povel 1995).

Imaging magnetograms are now available, with sensitivities down to a few Gauss in some cases (SVST in La Palma; Haleakala; and Taiwan). The extension to infrared wavelengths is very promising. Many advances in infrared solar physics are mentioned in the proceedings of the 15th Sac Peak meeting (see

I. Appenzeller (ed.), Reports on Astronomy, Vol. XXIIIA, 121–148.

Kuhn and Penn 1995). The NIM-2 imaging polarimeter provides 4 Stokes parameters at 1.5 μm (cf. Kuhn and Penn 1995; p87). Infrared detectors are now available up to 5 μm.

New large optical telescopes are presently under construction. The Dutch Open Telescope at La Palma, will be devoted to high resolution imaging. The French-Italian telescope THEMIS, evacuated and polarization-free, is expected to produce high resolution spectro-polarimetry (Rayrole et al. 1994). The long predisperser will be coupled with the echelle spectrograph to deliver, either multi-line additive spectroscopy, or subtractive imaging spectroscopy. The fast storage of data should enable THEMIS to perform a full spectro-polarimetry over solar areas with high time resolution. The associated Italian filter will produce high resolution imaging.

1.4. CORONA

At radio wavelengths, the spectrographs are characterized by an increasing number of channels, and yet the highest time resolution in solar physics (0.1 to 0.01s). Some instruments are new (Porto, Ondrejov, Thermopyles), many existing ones are renewed (Nançay Decameter Array, Trieste, Ondrejov, Zelenchuk). In the case of European instruments, more details can be found in a recent review by Krüger et al. (1995).

The imaging radio-telescopes are very efficient to locate solar sources, especially when a number of frequency channels provides 3-D data across the corona. New correlators allow fast 2-D mapping at the Nançay Radioheliograph (The Radioheliographic Group 1993), and synthesis softwares are now available at the SSRT (Irkutsk) and the Nobeyama Radioheliograph. VLA delivers high resolution data, BIMA observes at highest frequencies, and the OVRO antennas cover a large frequency range. A submillimetric telescope is under construction (Kaufmann et al. 1994)

In the optical range, the new generation instruments use super-polished mirrors. They produce achromatic images and allow multi-line spectral analysis. The MAC II coronagraph uses an annular field mirror as inverse occulting disk, and the MAC III project will include dust control. The CLEAR project, with large mirror and adaptive optics, can be used also for nighttime astronomy (cf. Kuhn and Penn 1995; p. 145).

The extension to infrared wavelengths is advantageous for coronal magnetic field measurements. The Evans coronagraph, using a 2-beams technique, is able to detect very low field intensities.

Regarding coronagraphy in space, many instruments are now available for observations in the UV and X-ray ranges, as well as in white light. In addition to missions performed by CORONAS and SPARTAN, continuous data are produced by YOHKOH. The TRACE instrument is in development phase. Since the launch of SOHO late 1995, its coronal instruments (SUMER, CDS, EIT, UVCS, LASCO and SWAN) deliver imaging and spectroscopy over a wide range of wavelengths. *In situ* measurements of the solar wind are performed by ULYSSES, and by the SOHO experiments CELIAS, COSTEP and ERNE (Fleck et al. 1995).

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2. SOLAR CYCLE: PERIODICITIES IN SOLAR ACTIVITY

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2.1. SHORT-TERM AND A QUASI BI-ANNUAL PERIODS.

Fractal theory suggests that solar activity varies irregularly on time scales longer than several days and shorter than a few months. Yearly values of fractal dimensions and bending points do not change in accordance with the solar cycle (Watari 1995). The fundamental solar rotation period of 25.5 days, which also is referred to as the period of the hypothetical "clock", was found to be pronounced in the analysis of the occurrence of major flares, in observations from the period from 1955 to 1991 (Bai and Sturrock 1993). Periods of the subharmonics in the range below 154 days, were found to be in agreement with periodicities found from analysis of flare occurrence times. Bai (1994) presented evidence for a 51-day periodicity in the occurrence rate of major flares, i.e. two times the fundamental period. A quasi-period of about 155 days was rediscovered in X-ray and Hα flares during Solar Cycle 21. Oliver and Ballester (1995) analyzed the 155 days periodicity in sunspot areas during cycle 22 (1986-1993). They did not detect the 155 day quasi-period, but they found evidence for a periodicity close to 86 days. Özgüc and Atac (1994) analyzed the flare index during the solar cycle 22 and discovered periods around 53 and 73 days. They also found that when the 73-day period, or the 155-day period, were present, the flare index correlated well with the relative sunspot number. The relation between polar faculae and sunspot cycles were studied in Kislovodsk solar observations from 1960 to 1994. The study showed strong fluctuations of polar faculae at a level of $\geq 1\sigma$ above the mean level, which correlates, but with the monthly sunspot area with a time delay of about 6 years (Makarov and Makarova 1996). A very strong modulation in the solar wind speed with an approximately 1.3 year period was detected in the data from the IMP-8 and Voyager-2 spacecraft. Combined with results from long-term auroral and magnetometric studies, this suggests that fundamental changes in the Sun occur on a roughly 1.3 year time-scale (Richardson et al. 1994).

The propagation of a quasi bi-annual impulse of the rotation residual from high latitudes towards the equator, during 1979-1981, was found by Gigolashvili et al. (1995). It was proposed that this event might be related with the reversal of magnetic polarity of the Sun in 1981. Periodicities in the solar differential rotation have been studied using Greenwich data during 1874-1976 (Javaraiah and Gokhale 1995). The temporal variations contain periods from 18.3 to 2.6 years. at levels $\geq 2\sigma$. Quasi bi-annual oscillations in the solar coronal index (CI), the Wolf number (W) and the universal time (UT) were deduced from observations (Djurovic and Pâquet 1993). The analysis suggested that there is a correlation between solar activity indices and variations in the rotation of the Earth.

2.2. THE 11 AND 22 YEARS CYCLES.

Carbonell et al. (1993) studied the north-south asymmetry of sunspot areas, in data from 1974 up to 1989, and found that the asymmetry could be represented by a multicomponent model made up of a long-term trend, i.e. with a period of 12.1 years which is very similar to that of the solar cycle, and a dominant, purely random component. Kariyappa and Sivaraman (1994) studied the variability of the solar chromospheric K-CaII network over the 11-year solar cycle. The authors showed that the area of the network elements is anti-correlated with the solar activity, and increasing by about 24% around solar minimum, compared to periods near maximum activity.

Zonal structure of large-scale magnetic field on the Hα charts, peculiarities of the polar magnetic field reversal, velocity of magnetic neutral line pole-ward migration, polar faculae activity, duration of 11-year cycles, high-latitude prominences areas, inclinations of the coronal streamers, all show that characteristic features of the odd 11-year cycle depend on those of the preceding even cycle in the period from 1870 to 1991 (Makarov 1994).

The long-term modulation of galactic cosmic rays at the ground-based detector energies, the monthly values of the neutron monitor and ionization chamber intensities have been correlated with sunspot numbers for each phase of sunspot cycles 18 to 22. Systematic differences have been found for odd and even 11-year cycles. During odd cycles the onset time of cosmic-ray modulation is delayed when compared with the onset time of the sunspot cycle, while they are more similar during even cycles (Storini et al. 1995)

2.3. LONG-TERM VARIATIONS.

Mouradian and Soru-Escaut (1995) studied the occurrence of flares and subflares during the period from 1964 to 1993, and compared their results with the activity of the Sun as whole. These authors found that the frequency of major flares exhibit a cycle period of 11-years, while subflares follow an 80-year cycle. Analyses of the total solar irradiance measurements obtained with the active cavity radiometer during the period 1984-1993, and by Nimbus-7 transfer cavity radiometer spacecraft during 1978-1993. This study confirmed the presence of an 11-year component in the irradiance variability which is found to follow the sunspot cycle. Their analyses also suggest the presence of a 22 and 80-year variability component (Lee et al. 1995). Lassen and Friis-Christensen (1995) studied the variations in the 11-year periods of solar activity over the past 5 centuries, and they found a period between 80 and 90 years. This changes in the solar cycle period were found to be strongly correlated with long-term variations in the global temperature of the Northern Hemisphere. The total carbonate and thermo-luminescence profiles in sea sediments core have been measured in the upper 200 cm of the core spanning the last 3100 years. The authors found the Gleisberg cycles at 83 and 92 years (Castagnoli et al. 1994).

Ribes and Nesme-Ribes (1993) presented a unique collection of 8000 daily sunspot observations recorded at the Observatoire de Paris from 1660 to 1719. Sunspot numbers, butterfly diagrams, active longitudes and rotation rates were compared with results from more recent observations. These newly available data may shed new light on the presence of 11-year cycle through the Maunder Minimum period.

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3. Solar Cycle: Statistical models of solar activity

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3.1. SOLAR CYCLE - STATISTICAL MODELS OF SOLAR ACTIVITY

This report gives an overview of some developments in statistical modeling of solar activity related to the solar cycle in the period 1993 to the present.

Solar activity displays two types of stochastic behavior. The first type is observed at small scales and at small time intervals and has a turbulent character. The modeling at these scales involves statistical methods specific for the description of systems with many or infinite degrees of freedom. The second type is related to the solar cycle and is a characteristic of whole-Sun long-term variations, such as Grand Minima of solar activity. The modeling of this chaotic behavior is carried out by the use of methods of low-dimensional dynamics such as the well-known Lorenz system.

To find the borderline between the two regimes of the stochastic behavior of the Sun Lawrence et al. (1996) examined the temporal scaling properties of solar magnetic activity on time scales from days to decades. They used more than 63,000 data points from the daily International Sunspot Number. By means of correlation analysis and both Fourier and wavelet spectral analysis, two regimes of temporal behavior of the magnetic variability have been distinguished. The scaling of the time series was analyzed in terms of multiplicative cascade processes which prove to be invariant over more than two decades of scale from about 2 years down to about 2 days or less. The authors interpreted this result as indicating generic turbulent structuring of the magnetic fields as they rise through the convection zone. A low-dimensional chaotic behavior in the sunspot number was found to be operating entirely at time scales longer than a transition threshold scale of about 8 years. This result gives observational support to the of concept studying the long-term behavior of the solar activity by the use of low-dimensional dynamical models and quantifies the limit of applicability of such models. Magnetic variability on time scales between 2 years and 8 years needs a special interpretation.

In a search for a chaotic behavior in solar activity Carbonell et al. (1994) analyzed the daily sunspot numbers for the period 1818-1990 and daily sunspot areas for the period 1874-1989. In contrast to the early findings by other authors, these authors came to the conclusion that these data are insufficient to determine a correlation dimension, K entropy and Lyapunov exponents for the solar activity because the saturation level, needed to obtain the correlation dimension by the Grassberger-Procaccia method, can not be achieved.

On the contrary, Rozelot (1995), who used the monthly sunspot data for the period 1749-1992 and a different approach, obtained a Lyapunov exponent about 0.05/year. This result implies that accurate forecast of solar activity over more than 4 years is not possible.

Kremliovsky (1994) constructed a one-dimensional non-linear recurrent function (W(i+1)=F(W(i)) where W(i) is a maximal value of the sunspot number in the cycle i) to describe the evolution of maxima of the 11-year cycle. The maxima of yearly averaged sunspot numbers for cycles -4 through 22, i.e. for the period 1700-1992 were used. The recurrent function has been interpreted as a Poincare map and approximated by an analytical formula. Application of a standard analysis to this one-dimensional dynamical system reveals the secular Gleissberg cycle, shows the known alternation of the even-odd maxima of activity, and indicates a phase catastrophe when a Grand Minimum, such as the Maunder minimum occurs. The duration of Grand Minima is a random variable with some characteristic distribution. This paper presents an interesting attempt to construct the chaotic dynamics directly from observational data. However, a number of assumption had to be made in this construction. One of the key assumptions, which greatly simplifies the problem, is that the map is one-dimensional.

Hoyng and Schutgens (1995) presented results of their study of the first two statistical moments of the magnetic field generated by the dynamo. The magnetic field was expanded in a set of eigenfunctions of the dynamo equation. The spectrum was found to be Lorenztian. An important assumption, that all real parts of the eigenvalues are negative had been made, however. This resulted in the statement that the first statistical moment of the magnetic field, i.e. its mean value, is zero. The apparent contradiction with the common use of the mean field in the standard dynamo models has to be resolved.

Early studies of solar activity focused on the search for periodicities such as the fundamental 11-year cycle and the 88-year secular Gleissberg modulation. Although the spectrum of solar activity is composed of a number of basic frequencies, these peaks are superposed on a background continuum. The earlier discovery of the Grand Minima of solar activity led to a question of the nature of the non-periodic part of the variations of the sun's activity. Ruzmaikin et al. (1994) addressed the question of whether or not the non-periodic continuum variations are produced by a white-noise random process. For that purpose the Hurst exponent, which characterizes the persistence of a time series, was evaluated for the series of C14 data for the time interval from about 6000 BC to 1950 AD. They found a constant Hurst exponent, suggesting that solar activity in the frequency range of from 100 to 3000 years includes an important continuum component in addition to the well known periodic variations. The calculated value of the exponent, $H \approx 0.8$, is significantly larger than the value of 0.5 that would correspond to variations produced by a white-noise process. This value is in good agreement with the results for the monthly sunspot data reported earlier, indicating that the physics that produces the continuum is a correlated random process and that it is the same type of process over a wide range of time interval lengths. By applying the same approach to the data on solar rotation Komm (1995) found close to the same value for the Hurst exponent.

A number of studies related to the solar cycle were also carried out in the stochastic (turbulent) region. Here just one study is mentioned.

Simon et al. (1995) developed kinematic models of turbulent diffusion generated by supergranulation at the solar surface. The models use current observations for the size, horizontal velocities and life-time of supergranules. Calculated diffusion coefficients range between 500 and 700 km^2 s^{-1} in agreement with the diffusion coefficient which gives the best fit in modeling the 11-year solar cycle. However, a disagreement between the observed (lower) diffusion coefficients and that predicted by the models, is not completely resolved. In particular, these models do not explain the magnetic field distribution in plages where a different value of the diffusion coefficient was observed.

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4. PHYSICS OF SUNSPOTS: DYNAMICS AND FINE STRUCTURE

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4.1. INTRODUCTION AND SUMMARY

Sunspots provide astrophysics with a means to observe in detail the interaction of a strong magnetic field with the plasma of a stellar atmosphere. Recent advances in capability both to resolve spatially some of the fine structure of sunspots and to make meaningful, *quantitative* measurements of the physical diagnostics of the solar plasma have resulted in dramatic changes in our observational understanding of sunspot penumbrae, thus providing solid observational benchmarks for theoretical studies of magneto-convection. Using these new data, we are converging toward a coherent picture for the observed magnetic real parts of the eigenvalues are negative had been made, however. This resulted in the statement that the first statistical moment of the magnetic field, i.e. its mean value, is zero. The apparent contradiction with the common use of the mean field in the standard dynamo models has to be resolved.

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4.1. INTRODUCTION AND SUMMARY

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4.2. THE 'CORRUGATED' PENUMBRAL MAGNETIC FIELD: LINK TO THE EVERSHED EFFECT

Very high resolution (≤ 1 *arcsec*) spectroscopy, imaging, and now precision polarimetry have revealed a 'corrugation' of the magnetic field in the penumbrae of sunspots. This corrugation has been alternatively dubbed 'fluting' (Title *et al.*, 1993), 'spines' (Lites *et al.*, 1993), or 'uncombed fields' (Solanki and Montavon, 1993). The average field of a sunspot penumbra tends to be more horizontal than vertical (Lites and Skumanich, 1990; Lites *et al.*, 1993; Skumanich *et al.*, 1994), but the penumbral field has been determined to undergo considerable fluctuation as a function of the azimuth angle about the center of the spot (Degenhart and Wiehr, 1991; Hofmann *et al.*, 1993; Title *et al.*, 1993; Lites *et al.*, 1993; Skumanich *et al.*, 1994). The earlier work by Degenhart and Wiehr indicated that these fluctuations are due primarily in the inclination of the field, with a tendency for stronger fields to be more vertical, and associated with brighter continuum features of the penumbra. The recent precision vector magnetometry (Lites *et al.*, 1993; Skumanich *et al.*, 1994) has revealed a very high anti-correlation of field strength with zenith angle, but also shows that the stronger fields of such spines diverge away from the axis of the spine (which is usually oriented radially from the center of the sunspot), as would be expected of a buoyant magnetic field residing in the highly stratified solar photosphere. This structure heralds an important property of magneto-convection: apparently such a corrugated structure for the field is a quasi-stable equilibrium (spatial structure of the vector magnetic field seems to persist nearly unchanged for at least 1/2 hour, Lites *et al.* 1993) of the penumbral atmosphere within which significant vertical transport of radiative energy is taking place, presumably as a result of magneto-convective transport below the surface.

The connection of the Evershed flow with the observed fine structure of the vector field has only emerged within the last few years. Over the past two decades there has been considerable debate regarding the association of the Evershed flow with bright or dark penumbral features. It now appears that the outflow *is* associated with the darker penumbral features, which are also those whose field is oriented most horizontally. Excellent spatial resolution (≤ 0.5 *arcsec*) is absolutely necessary to discern this relationship (Wiehr and Degenhardt, 1994). Also apparent from the recent observational studies of spectral lines forming at various heights in the solar photosphere, and from asymmetries of those lines (Wiehr and Degenhardt, 1992; Rimmele, 1994; Degenhart and Wiehr, 1994; Wiehr and Degenhardt, 1994; Wiehr, 1995), is the fact that the Evershed Doppler flow does not extend vertically beyond a few scale heights above the observable penumbral surface. However, especially near the outer edge of the penumbra, the Evershed flow appears to be slightly elevated above the continuum (Rimmele, 1995a). The issues of both angular resolution of observations and height dependence of the Evershed Doppler shift probably account for contradictory results of many prior studies of the correlation of Evershed Doppler shifts with intensity structures of the photosphere, and may thus explain the lack of correlation of dark continuum features and magnetic field structures found in some recent observations of very high angular resolution (Lites *et al.*, 1990; Johannesson, 1993).

Independently, Rimmele (1994) and Shine *et al.* (1994) discovered that the Evershed motions, when observed at high resolution, are not steady flows. Excursions of larger radial Doppler shift appear to propagate outward from the inner penumbra with proper motions of about 3-4 km/s. These fluctuations may have rather large amplitudes (up to 6 km s^{-1}, Rimmele 1994) but they are superimposed on a steady flow of 1-2 km s^{-1}. The time history of Doppler shift at a selected point in the outer penumbra shows an "irregular repetitive behavior" with recurrence approximately every 10-15 min. This is the likely source of the oscillatory power of the outer penumbra detected earlier (see review by Lites, 1992), which now appear *not* to be associated with the 'running penumbral waves' observed in the penumbral chromosphere. The Evershed flow extends well beyond the white-light outer penumbral boundary (Solanki, Montavon, and Livingston, 1994; Rimmele, 1995b), but this extension is only observed in lines formed somewhat above the base of the photosphere. The Evershed flow thus appears to be confined to a ribbon having a rather narrow extent, perhaps only one scale height in the vertical direction (Rimmele, 1995a), and remains nearly parallel to the surface at very low altitude for considerable distances away from the spot.

The observational picture now emerging of the sunspot penumbra is then the following: A time variable outflow of material is confined to the nearly horizontal (and weaker field) component of the corrugated penumbral field, which is associated with the darker structures seen in the continuum intensity. The more vertical spines of the penumbral corrugation, representing the stronger field regions, will 'merge' together at some height above the photosphere causing a rapid reduction of the area filling factor for the weaker, horizontal component (thus also for the Evershed flow) with height. The spines may be associated both with extended structures observed in L. Golub's NIXT X-ray images, which appear to connect the penumbra of a sunspot to plage regions at great distances, and also with the 'inverse Evershed flow' of the overlying chromosphere: an inflowing motion toward the sunspot visible in chromospheric lines both within the outer penumbra and extending well outside of the photospheric penumbral boundary.

4.3. THEORETICAL UNDERSTANDING OF PENUMBRAL MODELS

Convective processes in the presence of strong magnetic fields are the most probable cause for the fine scale structure and dynamics of sunspots. In the case of the Evershed flow, standard concepts of convection, especially overturning convection, are probably not applicable, but convection is responsible for setting the conditions that cause the flow. Precisely how this processes proceeds is not yet clear. The newly discovered repetitive variability of the Evershed effect, when observed at small scales, may be an important clue to this process. Such behavior might lead one to suspect that the Evershed flow is a wave phenomenon, but this an interpretation is surely not correct in view of the observed properties of the flow (Bünte and Solanki, 1995; Thomas, 1994; Rimmele, 1994). The most attractive mechanism for Evershed motion remains the siphon flow model (Thomas and Montesinos, 1993). Questions remain for this model: where do these flows return to the photosphere outside of the sunspot, and how does the temporal variability of the Evershed flow fit with this model? The corrugation of the field within the penumbra, indicating the presence of a field component which is nearly horizontal for great distances, relieves many concerns surrounding mass conservation and variation of the flow speed with height in siphon flow models. New observations verifying the presence of a 'canopy' of magnetic field outside the sunspot (Solanki *et al.*, 1992; Title *et al.*, 1993; Lites *et al.*, 1993), along with the height variation of the flows near and beyond the penumbra-photosphere boundary (Rimmele, 1995b), suggest that siphon flows could continue at low altitude for considerable distance away from the spot. The slowness of fluctuations in the observed intensity structure and magnetic fields of sunspots suggest that interchange convection is not, in its simplest form, operative in sunspot penumbrae (Rimmele, 1994). Why the Evershed channels appear dark in the continuum, considering that they are evidently elevated structures of quite thin vertical extent, and indeed weaker in field strength, also remains an open question. Finally, studies of the asymmetries of the polarization of line profiles suggest that the penumbral atmosphere may be structured on size scales much smaller than have yet been observed (Sánchez Almeida *et al.*, 1996).

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5. PHYSICS OF SUNSPOTS: MAGNETO-CONVECTION AND FLUX TUBE MODELING

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5.1. INTRODUCTION

Our understanding of the nonlinear interaction between magnetic fields and convection at the surface of the Sun has made great progress in the last three years. New high-resolution observations of photospheric magnetic fields, with sub-arcsecond resolution (e.g. Sobotka, Bonet & Vázquez 1993; Muller 1994; Berger et al. 1995; Wang et al. 1996), have been accompanied by the availability of supercomputers that allow realistic simulations of three-dimensional behavior (Nordlund, Galsgaard & Stein 1994; Brummell, Cattaneo & Toomre 1995). As a result of these technical advances, it has at last become possible to compare theoretical models with actual observations. This summary of recent work will focus first on idealized models and then on more ambitious simulations, before confronting numerical results with the behaviour of magnetic fields in the solar photosphere.

5.2. IDEALIZED NUMERICAL EXPERIMENTS

The aim of these calculations is to describe simplified models of nonlinear magneto-convection so that the effects of different physical processes can be isolated. More recent studies of two-dimensional magneto-convection have therefore concentrated on specific features. Compressible convection (with or without a magnetic field) frequently develops into streaming motions; the development of shearing instabilities, including a new family of pulsating waves (Matthews et al. 1993), is associated with a complicated sequence of bifurcations, which has been explored in considerable detail for the two cases when the imposed field is vertical, as at the center of a sunspot (Proctor et al. 1994), and when it is horizontal (Lantz & Sudan 1995; Lantz 1995; Brownjohn et al. 1995). When the field is oblique, as in the penumbra, it supports traveling waves whose sense of motion depends upon the inclination of the field to the vertical, and is consistent with the inward motion of bright filaments and the outward motion of dark features, where fields are more steeply inclined (Hurlburt, Matthews & Proctor 1996). Other computations have investigated twisting of magnetic fields in an axisymmetric cell (Jones & Galloway 1993) and the consequences of parameterizing subgridscale diffusion (Fox, Theobald & Sofia 1993).

In three dimensions, the corresponding numerical experiments have primarily been concerned with pattern selection in the nonlinear regime. Weakly nonlinear theory suggests that, while two-dimensional traveling waves survive in three dimensions, standing waves give way to alternating rolls (Clune & Knobloch 1994). This prediction has been confirmed for magneto-convection in a shallow stratified layer (Matthews, Proctor & Weiss 1995) and the alternating rolls are found to be periodically modulated and, eventually, chaotic as the vigor of convection is increased. A separate investigation of convection in a deep stratified layer has explored the effect of varying the imposed field strength (Weiss, Matthews & Proctor 1996): at the upper boundary of the convecting region, weak fields are confined to a network that encloses the broad rising plumes, and magnetic flux moves rapidly between junctions as this network evolves; as the field is increased, the horizontal scale of convection is reduced and motion becomes more ordered until the rising plumes eventually form a steady quasi-hexagonal pattern enclosed by a weak magnetic network above the sinking gas. These spatiotemporal structures are related to the behaviour of weak fields in intergranular lanes and of umbral convection, respectively.

Turbulent magneto-convection in a rotating layer can act as a self-exciting dynamo, so there is no need to include an external field. In a more elaborate model the violently convecting region lies above

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Turbulent magneto-convection in a rotating layer can act as a self-exciting dynamo, so there is no need to include an external field. In a more elaborate model the violently convecting region lies above a stable layer, and the flow is dominated by a swirling downdraft. The field lines are wrapped around this plume and follow the vortex as it moves (Nordlund et al. 1994; Brandenburg 1994; Brandenburg et al. 1996). The structure of such turbulent fields remains a controversial topic (Nordlund et al. 1994), stimulated by the growth of interest in fast dynamos (Childress & Gilbert 1995). Whether magnetic fields within the solar convection zone are confined to isolated flux tubes, as they are at the surface, or are intermittent but space-filling, as in certain models (Vainshtein et al. 1993) has yet to be determined.

5.3. FORMATION OF FLUX TUBES

In the models already described flux concentrations form at corners in the convective network and persist to a depth that depends on the choice of lower boundary conditions. This process has been investigated in a series of increasingly sophisticated calculations, incorporating radiative transfer (Grossmann-Doerth et al. 1994; Steiner et al. 1994). In these two-dimensional models a flux sheet forms between two convection rolls; where the field is strong the density is reduced but 'convective collapse' is not a separate phenomenon. Seen as a video, these results are extremely convincing. The flux sheet is violently active and the structure of the visible photosphere above it is consequently affected.

On a much larger scale, Caligari, Moreno-Insertis & Schüssler (1995) have investigated the origin of the magnetic flux that emerges as a rising Ω-loop in active regions and in sunspots, and have described the associated instabilities of a thin toroidal flux tube in the convection zone (Ferriz Mas & Schüssler 1993, 1994, 1995; Schüssler et al. 1994). These instabilities are driven by magnetic buoyancy, which is responsible for liberating flux from the deep-seated field produced by the solar dynamo (Schüssler 1993; Matthews, Hughes & Proctor 1995).

5.4. COMPARISON WITH OBSERVATIONS

At the simplest level, kinematic modeling of granular and supergranular convection provides a means of estimating the rates at which magnetic fields diffuse (Simon, Title & Weiss 1995) and yields results that can be compared with observations such as those of Simon et al. (1994). Dynamical simulations are more impressive, and one of the most promising features of the flux sheet model is that radiation diagnostics can actually be computed (Steiner et al. 1996). Three-dimensional calculations are beginning to generate results that are numerically resolved and can be related to observed properties of plages and of umbral convection in a sunspot. The penumbra poses a more difficult problem: it is clear from global models that a new form of filamentary convection is involved, and that this is responsible for carrying energy inwards from the surrounding field-free plasma, to be radiated from the photosphere above the penumbra (Jahn & Schmidt 1994; Rucklidge, Schmidt & Weiss 1995). Although the motion of an individual flux tube has been successfully computed (Jahn, Schlichenmaier & Schmidt 1996) a proper model of penumbral convection has yet to be constructed.

We can expect rapid progress in the next three years. Simultaneous optical, X-ray and ultraviolet observations will provide a much clearer picture of magnetic fields and convection in the photosphere; meanwhile massively parallel computers will facilitate the development of models of fully turbulent magnetoconvection that can bear direct comparison with the observations. Then we shall be able to reliably predict the structure of magnetic fields below the surface, at levels where they cannot be observed. This is an exciting prospect.

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6. FILAMENTS AND PROMINENCES

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6.1. FORMATION AND SUPPORT

Empirical models, synthesized from different kinds of observations, arrive at conflicting views about the formation of prominences. Focusing on patterns of fine-scale Hα fibrils which define filament channels and which link the barbed edges of filaments with adjacent weak photospheric fields, Martin et al. (1994) and Martin and Echols (1994) view the process as a surface phenomenon controlled primarily by canceling magnetic flux at a polarity inversion. Rust and Kumar (1994) give more weight to the hemispheric asymmetry in the handedness of the helicity of filaments and filament channels and to evidence favoring twisted flux ropes - including erupting filaments - to propose that filaments emerge already twisted by a global, subsurface velocity pattern.

Priest et al. (1996) account for the coherent organization in filaments and filament channels revealed by Martin and coworkers by combining the effects of differential rotation on subsurface flux, of magnetic buoyancy to raise the flux to the surface, and of reconnection to rearrange the flux as a filament channel with magnetic field oriented along its axis. Low and Hundhausen (1995) propose that the filament channel is the manifestation of a flux rope in the chromosphere (see also Rust and Kumar 1994; Filipov 1995). Their magneto-static model demonstrates an intimate relationship between the prominence and its coronal cavity.

Attempts to create a magnetic 'hammock' to support the mass of a prominence include: modeling static flux tubes by balancing radiative losses and mechanical heating while neglecting heat conduction in the coronal energy balance (Degenhardt and Deinzer 1993); initiating a massive siphon flow from the chromosphere into a background in magneto-thermal equilibrium (Drake et al. 1993), or into two isothermal regions (Del Zanna and Hood 1996); taking advantage of the naturally occurring dip in a

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6. FILAMENTS AND PROMINENCES

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6.1. FORMATION AND SUPPORT

Empirical models, synthesized from different kinds of observations, arrive at conflicting views about the formation of prominences. Focusing on patterns of fine-scale Hα fibrils which define filament channels and which link the barbed edges of filaments with adjacent weak photospheric fields, Martin et al. (1994) and Martin and Echols (1994) view the process as a surface phenomenon controlled primarily by canceling magnetic flux at a polarity inversion. Rust and Kumar (1994) give more weight to the hemispheric asymmetry in the handedness of the helicity of filaments and filament channels and to evidence favoring twisted flux ropes - including erupting filaments - to propose that filaments emerge already twisted by a global, subsurface velocity pattern.

Priest et al. (1996) account for the coherent organization in filaments and filament channels revealed by Martin and coworkers by combining the effects of differential rotation on subsurface flux, of magnetic buoyancy to raise the flux to the surface, and of reconnection to rearrange the flux as a filament channel with magnetic field oriented along its axis. Low and Hundhausen (1995) propose that the filament channel is the manifestation of a flux rope in the chromosphere (see also Rust and Kumar 1994; Filipov 1995). Their magneto-static model demonstrates an intimate relationship between the prominence and its coronal cavity.

Attempts to create a magnetic 'hammock' to support the mass of a prominence include: modeling static flux tubes by balancing radiative losses and mechanical heating while neglecting heat conduction in the coronal energy balance (Degenhardt and Deinzer 1993); initiating a massive siphon flow from the chromosphere into a background in magneto-thermal equilibrium (Drake et al. 1993), or into two isothermal regions (Del Zanna and Hood 1996); taking advantage of the naturally occurring dip in a quadrupolar magnetic region, such as formed by two approaching bipolar regions, to model an inverse polarity prominence (Demoulin and Priest 1993) or a normal-polarity prominence (Lepeltier and Aly 1994) by introducing line currents; supporting a current sheet of finite height and of constant axial current density inside a twisted flux tube (Cartledge and Hood 1993); by solving for the 3-dimensional shapes of strongly sheared field lines concentrated next to the polarity inversion line of a point dipole buried below the photosphere (Antiochos et al. 1994). Stability criteria for models of prominences have been investigated for a variety of equilibria by de Bruyne and Hood (1993), Drake et al. (1993), Aly et al. (1994), Longbottom and Hood (1994), Longbottom et al. (1994), Strauss and Longcope (1994).

6.2. RADIATIVE TRANSFER

Gouttebroze et al. (1993) created a grid of 140 simple models describing the emission from hydrogen lines and continua over a wide range of physical conditions usually assumed for prominences. Their computations use a 20-level plus continuum hydrogen atom and include the effects of partial redistribution in the Lyα and β lines. Their aim is to provide observers with simple diagnostics to interpret data on intensity ratios, line widths, etc., and to provide theorists with a benchmark for testing similar models or developing more sophisticated ones. Heinzel et al. (1994) extended this study to calculate 24 correlations to apply to prominence observations. Heinzel (1995) also developed a new NLTE transfer code for 1-D isolated, externally irradiated, atmospheric structures, based on the multilevel accelerated lambda iteration (MALI) technique. Numerical tests compared to earlier benchmark results run much faster without a significant loss in accuracy. With this new code Heinzel et al. (1995) show that the commonly observed bright rims on filaments can be explained by the effects of radiative diffusion of the Hα line in a 1-D slab parallel to the solar surface and irradiated from below.

In anticipation of spectroscopic demands from observations made by SOHO and THEMIS, numerical codes are under development for 2-D radiative transfer in prominences, with a two-level atom model with PRD effects included (Auer and Paletou, 1994), and with a five-bound level hydrogen atom including PRD (Paletou, 1995).

6.3. DYNAMICS AND FINE STRUCTURE

In comparing two kinds of 'disparition brusques' (DBs) of quiescent filaments with CMEs - the dynamic (DBd) kind more commonly seen on the limb (see Korobova et al. 1996 for an exception) and the thermal (DBt) kind seen mainly on the disk - Mouradian et al. (1995) find that only the DBd are associated with CMEs, thus compromising statistical studies which compare total numbers of DBs with CMEs. Ofman and Mouradian (1996) find that present observational evidence is qualitatively consistent with resonant absorption of Alfven waves as the heating mechanism driving DBt. Vrsnak et al. (1993) followed the evolution of the helical threads in a Dbd at the limb and conclude that although the pitch angle of isolated threads decreased with time, the total twist did not change. The total radio flux from a spatially resolved erupting prominence observed simultaneously in microwaves (17 GHz), soft X-rays, and Hα by Hanaoka et al. (1994) changed little during the eruption. This implies that each thread of the prominence did not expand along with the entire structure. Multifrequency observations at millimetric wavelengths of an erupting prominence by Irimajiri et al. (1995) confirm that the filling factor decreased during the eruption whereas emission measures and electron densities were nearly steady.

Long period (40 - 80 min) velocity oscillations in prominences are dependent on heliolatitude according to Bashkirtsev and Mashnich (1993). Mashnich et al. (1993) confirm the existence of short period (2 - 10 min) oscillations and claim a transformation towards longer periods with height in prominences. Simultaneous observations of oscillations in the same prominences with two solar telescopes by Balthasar et al. (1993) confirm the solar origin of periods near 12 and 20 min, deny any systematic trend of periods with height, and find oscillations in one prominence at a period near 30 s predicted by theory. Joarder and Roberts (1993b) identified the possible modal types of oscillation of a slab-shaped prominence embedded in a uniform line-tied magnetic field. The periods of fundamental magneto-acoustic modes change only slightly when simple models include the effects of stratification and field-line curvature (Joardar and Roberts (1993a). Oliver and Ballester (1995) investigated magneto-acoustic gravity modes of vibration in an inhomogeneous medium wherein temperature and density pass smoothly from prominence to coronal values.

6.4. PROMINENCE FINE STRUCTURE

The following results were inferred from spectroscopic investigations of quiescent prominences at high spatial and spectral resolution with the Gregory Coude Telescope at Observatorio del Teide: (1) the lower temperatures of cool prominences require a denser packing of fine threads thereby reducing the penetration of the He exciting UV radiation (Stellmacher and Wiehr 1994a); (2) individual emission features originate in closely tied bundles of threads (Stellmacher and Wiehr 1994b); (3) He excitation is enhanced in structured prominences of low Balmer brightness or outer parts of unstructured bright prominences (Stellmacher and Wiehr 1995); the long-term (4 hr) behavior of line intensities and line ratios indicate the probable dissolution of a prominence as the density of fine structures decreases (Balthasar and Wiehr 1994). Mein et al. (1994) fit statistical samples of measured Hα intensities and Doppler shifts of a well-resolved quiescent prominence at disk center to a model in order to estimate the maximum number of threads and the mean values for their optical depths, source functions, upward velocities, and velocity distribution. Yi and Molowny-Horas (1995) applied Local Correlation Tracking to digitized Hα images of high spatial resolution to investigate transverse chromospheric motions at a large filament, finding mainly low velocities (1 km s^{-1}), with some fast (>100 km s^{-1}), short-lived features.

Steele (1996) modified an earlier 2D model to include vertical variations in the threads comprising a prominence. Gray and Brown (1996) devised an analytical model of a filamentary structure in a prominence (or flare) which exhibits the small spatial scales necessary to produce a thermal gradient large enough to give cross-field thermal conduction a dominant role in governing the number and size of the threads in the prominence (or flare).

6.5. FILAMENTS AND THE SOLAR CYCLE

Mouradian and Soru-Escaut (1994) classified nearly 6000 filaments according to two basic types: those separating areas of opposite magnetic polarity belonging to one and the same bipolar region (Type A), and those separating opposite polarities belonging to two separate bipolar regions (Type B). They find two simultaneous cycles of filaments present at all times, one increasing (for the B-type), the other decreasing (for the A-type). Rust and Martin (1994) found a direct correspondence between the vortical sense of sunspot whirls and the 'handedness' of associated filaments considered as helices. The handedness of filaments and the vortical sense of sunspots have a hemispheric dependence that does not change with cycle number.

6.6. PLASMA DIAGNOSTICS

Foukal and Behr (1995) measured electric fields between 2 and 5 V/cm using Stark-sensitive H I emission lines in 9 bright quiescent prominences; these low measured values are not easily reconciled with a current sheet model of prominences. Casini and Foukal (1996) calculated Stark-polarized profiles for H I lines observable in prominences at visible and infrared wavelengths; they draw attention to the high sensitivity to electric fields of high-level transitions at wavelengths around 11 μm.

By measuring linear polarization simultaneously in two lines, Bommier et al. (1994) determined completely the magnetic field vectors and electron densities in 14 quiescent prominences near the limb. Twelve were found to be of inverse polarity - all remote from active regions - ten being polar crown prominences. From these new data Anzer (1995) constructed prominence models in magneto-hydrostatic equilibrium which are on average more massive and considerably narrower than older ones. Heinzel at al. (1996) also took the polarimetric data of Bommier et al. to derive the true geometrical thickness for several quiescent prominences, using the integrated Hα intensity to obtain the emission measure from the correlations calculated by Gouttebroze at al. (1993).

UV spectra at high spectral and spatial resolution of two quiescent prominences analyzed by Wiik et al (1993) reveal striking differences related to the state of activity in these structures. Spectra of the more active prominence are dominated by transition-zone lines (10^5 K) with high bulk flows and non-thermal velocities; the more stable prominence shows cooler chromospheric lines ($2\ 10^4$K) with weak bulk flows. Strong variations in intensity and Doppler shifts occur on scales 1700 km, while combined density and emission measures and optical depths indicate much smaller path lengths, implying the presence of structures on spatial scales of a few hundred km.

With the FTS spectrometer at NSO/Kitt Peak Chang and Deming (1996) detected emission lines in a prominence of hydrogen and helium in the near infrared (1 - 5 microns). They found the helium lines to be formed in a cooler plasma than the hydrogen lines, thereby concluding that the helium lines are formed inside the central part of the prominence while the hydrogen lines are formed around its edges.

At 850 μm, Bastian et al. (1993) found that Hα filaments have low contrast relative to the quiet background and are optically thin. They attribute the reduced brightness to either reduced heating, a small effective density scale height, or both, but not to an overlying coronal cavity or any absorbing matter.

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7. SOLAR FLARES: MAGNETIC FIELD AND ELECTRIC CURRENTS IN FLARE REGIONS

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Storage and release of energy in solar flares can be described in the picture of magnetic field or electric current.

7.1. EVIDENCE FOR MAGNETIC SHEAR

The development of magnetic shear in emerging new magnetic flux of opposite polarity (in δ regions) has been mapped by vector magnetographs (Lites et al. 1995) and (Zhang 1995a). The definition of shear angle between the observed magnetic field and the corresponding current-free field was made by Lu et al. (1993). J. Wang (1994) discussed possible models describing the development of magnetic shear in solar flare producing regions. The flares occurred near the region of large magnetic shear, but not at the location of maximum shear or maximum magnetic field (Fontenla et al. 1995). H.N. Wang (1995) analyzed the relationship between the occurrence of flares and longitudinal magnetic field caused by the emergence of the magnetic flux. Shi and Wang (1994) pointed out that all δ-region sunspots formed as a result the emergence of two different dipoles, and δ-region sunspots themselves could undergo flux cancelation and disintegration. Gaizauskas et al. (1994) presented a case study of shear-related flare activity created by the sudden disruption of the f-polarity, of the umbral component of a δ-sunspot. The observational data from the international campaign of June 1991 were presented by Schmieder et al. (1994). Precise measurements of sunspot motions in a super active region observed at Debrecen, together with Tokyo white-light pictures, demonstrated how fragmentation may lead to a continuous restructuring of the magnetic field pattern. On the other hand, rapid changes are evidence for rapidly emerging, new flux. This, in turn, leads to shearing of the field lines and storage of magnetic energy.

A puzzling result is that the magnetic shear in the photosphere may show no decrease as a result of a flare, as implied by most magnetic models. Actually, it may be found to increase (Hagyard et al., 1993; Ambastha et al., 1993; H.M. Wang et al., 1994; Chen et al. 1994b; Zhang et al., 1994). This suggests that solar flares do not release all the stored energy in the twisted magnetic field. Shi et al. (1995) found a high degree of magnetic shear at or close to the separatrices, where the transverse field changes its alignment.

7.2. EVIDENCE FOR NON-POTENTIAL MAGNETIC FIELD

Vertical shear in the transverse component of the magnetic field was observed in a large δ-sunspot group (Zhang, 1995b). Chromospheric Hβ and photospheric Fe I λ5324 magnetograms show anti-correlations of polarity at coincident positions in active regions. Possible non-potential local magnetic features have been proposed by Li et al. (1994) and Liu et al. (1995). Active region He I filaments lie on polarity inversion of the longitudinal chromospheric magnetic field (Penn and Kuhn 1995). Determination of the real chromospheric magnetic patterns is difficult due to the departure of the chromosphere from local thermal equilibrium and to blends of photospheric lines in the wings of the selected chromospheric lines (Zhang 1993).

The configuration of magnetic fields has been studied from observations of photospheric vector magnetograms, from Hα filtergrams and soft X-ray images. Schmieder et al. (1993) analyzed the time evolution of Hα surges, C IV brightenings and X-ray spikes, and demonstrated that the energy source is very likely magnetic reconnection. The Yohkoh X-ray images provide important new information about the structure of magnetic fields in the corona. Kurokawa et al. (1994) found successive emergence of twisted bundles of magnetic loops associated with photospheric magnetic shear in a flare producing region. Moore et al. (1994) found, from superposition of Yohkoh X-ray images on MSFC photospheric vector magnetograms of active regions, that the coronal heating is enhanced at sites of strong magnetic shear, and that this heating is associated with micro-flaring activity. van Driel-Gesztelyi et al. (1996) found that X-ray bright point flares are result from magnetic reconnection between the emerging and the pre-existing field.

The observation of the Na I $\lambda 5896$ chromospheric vector magnetic field demonstrated that the field becomes force-free about 400 km above the photosphere (Metcalf et al. 1995). A force-force field model based on observed photospheric vector magnetograms was presented by Yan and Wang (1995) and Yan et al. (1995), supporting the suggestion that the powerful flares in the super-active region (NOAA 6659) are probably were to interaction between an energetic low-laying active magnetic loop along the magnetic neutral and several other loops. This is in agreement with the suggestion by Zhang and Wang (1994). From their analysis of two-ribbon eruptive flares, Moore et al. (1995) found that the sheared field in the pre-flare phase contained sufficient non-potential magnetic energy to power the flares. Magnetic field dissipation is, furthermore, assumed to occur in the MHD turbulent reconnection wall. The magnetic reconnection probably takes place in the lower atmosphere (J. Wang 1995) where cancelation of magnetic fields of opposite polarity occurs.

7.3. INDIRECT EVIDENCE OF ELECTRIC CURRENTS

Several studies have been conducted in order to resolve the 180°-ambiguity of the direction of the transverse field (e.g. Li et al., 1993; H.N. Wang and Lin, 1993; Metcalf, 1994; Gary and Demoulin, 1995), and to measure vertical electric currents in active regions in the photosphere.

The observational results demonstrate that the emergence of magnetic flux of opposite polarity in δ-sunspot groups is associated with the generation of electric currents (Zhang, 1995a). Daily maps of vertical electric current in solar flare regions, inferred from photospheric transverse magnetic field in the heliographic plane, in solar flare regions supply information on the energy transport from the sub-atmosphere to the corona (T. Wang et al. 1994; Zhang, 1995c, and also Fontenla et al. 1995). The change or enhancement of vertical electric current during the flares was analyzed by Lin et al. (1993) and Wang J. et al. (1996). The results from these studies indicate that Hα or Hβ flare kernels do not always occur near the peaks of electric currents. van Driel-Gesztelyi et al. (1994) showed that the Hα flare kernels and the main electric current cells in the photosphere are located close to the intersections of the separatrices with the chromosphere, at least in a linear force-free field model based on the observed shear.

7.4. GENERATION OF ELECTRIC CURRENTS

A possible mechanism for generation of electric currents in the photosphere was inferred from observations of the magnetic field (Zhang, 1995a). The evolution and characteristic time of the current helicity in active regions was presented by Pevtsov et al. (1994; 1995). These are connected with transport of the magnetic energy from the sub-atmosphere to the upper atmosphere (J. Wang 1996). However, ideas about the distribution of electric currents in the corona are generally based on theoretical studies. Xu and Wu (1995) and Tang et al. (1996) analyzed models of filament currents and their stability. Melrose (1995) calculated electric current paths in the corona and argued that the electric current cannot be generated by shearing motions in the photosphere and that the currents must close in the sub-photospheric layers. Melrose also suggested that there is a relationship between the release of energy in solar flare and changes of electric currents in the corona.

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8. SOLAR FLARES: PARTICLE BEAMS AND ACCELERATION PROCESSES

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Progress in the understanding of acceleration processes and particle beams in solar flares has been greatly stimulated over the last 3 years by hard X-ray and gamma ray observations from recent space missions (*COMPTON Gamma Ray Observatory CGRO*, *Yohkoh*, *Ulysses*, *GRANAT*, *GAMMA-1*), and by an increased number of coordinated ground-based observations at metric/decimetric radio wavelengths, e.g. with the *Very Large Array (VLA)*, *Nancay Radioheliograph*, and the digital radio-spectrographs of *ETH Zurich*, *Tremsdorf*, and *Ondrejov*. In the following we report on a few recent developments and highlights. For a more complete account we refer to reviews and summaries referenced in the last section.

8.1. THEORY AND ACCELERATION PROCESSES

Recent interest in theoretical studies of particle acceleration processes relevant to solar flares is focused on (1) stochastic acceleration, (2) electric DC field acceleration, and (3) shock acceleration.

Stochastic electron acceleration has been modeled in terms of gyro-resonant interactions occurring in MHD-turbulent cascades (Miller, LaRosa, & Moore 1996), but was found to be equally efficient for protons or ions (Miller & Roberts 1995). This mechanism is believed to operate in MHD-turbulent regions like in reconnection outflows (LaRosa, Moore, & Shore 1994).

Alternatively, electric DC field models with electron runaway acceleration have been further tested by fitting to observed HXR spectra (Benka & Holman 1994), but satisfactory fits tend to require a super-hot thermal component. Besides the lack of a plausible scenario to generate large-scale DC electric fields in

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8. SOLAR FLARES: PARTICLE BEAMS AND ACCELERATION PROCESSES

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Progress in the understanding of acceleration processes and particle beams in solar flares has been greatly stimulated over the last 3 years by hard X-ray and gamma ray observations from recent space missions (*COMPTON Gamma Ray Observatory CGRO*, *Yohkoh*, *Ulysses*, *GRANAT*, *GAMMA-1*), and by an increased number of coordinated ground-based observations at metric/decimetric radio wavelengths, e.g. with the *Very Large Array (VLA)*, *Nancay Radioheliograph*, and the digital radio-spectrographs of *ETH Zurich*, *Tremsdorf*, and *Ondrejov*. In the following we report on a few recent developments and highlights. For a more complete account we refer to reviews and summaries referenced in the last section.

8.1. THEORY AND ACCELERATION PROCESSES

Recent interest in theoretical studies of particle acceleration processes relevant to solar flares is focused on (1) stochastic acceleration, (2) electric DC field acceleration, and (3) shock acceleration.

Stochastic electron acceleration has been modeled in terms of gyro-resonant interactions occurring in MHD-turbulent cascades (Miller, LaRosa, & Moore 1996), but was found to be equally efficient for protons or ions (Miller & Roberts 1995). This mechanism is believed to operate in MHD-turbulent regions like in reconnection outflows (LaRosa, Moore, & Shore 1994).

Alternatively, electric DC field models with electron runaway acceleration have been further tested by fitting to observed HXR spectra (Benka & Holman 1994), but satisfactory fits tend to require a super-hot thermal component. Besides the lack of a plausible scenario to generate large-scale DC electric fields in flare loops in the first place, they require also anomalous resistivity to accelerate particles to gamma-ray energies, and are not capable of reproducing fast fluctuations on subsecond time scales, as observed in hard X-rays (Machado et al. 1993; Talon et al. 1993; Vilmer et al. 1994; Aschwanden et al. 1995a).

Particle acceleration in shock waves was mainly applied to reconnection outflows (Hirayama 1994), to coronal mass ejection (CME)-driven shocks (Kahler 1994), or to quasi-parallel shocks that produce radio type II bursts (Mann & Classen 1995).

8.2. ELECTRON TIME-OF-FLIGHT MEASUREMENTS

A breakthrough in the diagnostics of propagating electrons in flare loops has been achieved with energy-dependent timing measurements of hard X-ray time structures observed with the most sensitive *BATSE/C* detectors. It was discovered that subsecond hard X-ray pulses show energy-dependent time delays in the order of 10-100 ms that correspond to the expected time-of-flight differences of relativistic electrons, and thus allow to determine the flight distance between the coronal acceleration site and the chromospheric energy loss site (Aschwanden et al. 1996a). Comparing these *CGRO* timing measurements with soft and hard X-ray images from *Yohkoh*, a scale-invariant ratio of $l/s = 1.4 \pm 0.3$ was found for the ratio of the electron time-of-flight distance l to the loop half length s, valid over a large range of loop sizes (Aschwanden et al. 1996b).

8.3. LOCALIZATION OF ACCELERATION SITES

Another surprising discovery was made by Masuda et al. (1994), who detected with the *Hard X-ray Telescope (HXT)* on *Yohkoh* ≥ 30 keV HXR sources in the cusp region above the flare loop top in some flares. These cuspal HXR sources appeared in addition to the common double footpoint sources. Sakao (1994) analyzed the simultaneity of conjugate footpoint HXR sources and found that they were coincident within ≤ 0.1 s. The simultaneity of conjugate footpoints together with the measurements of the electron time-of-flight distances provide strong constraints that the acceleration site is most likely located in the cusp region above the flare loop, as envisioned in magnetic reconnection models.

8.4. TRACING OF ELECTRON BEAMS

A natural consequence of cuspal acceleration sites is the bi-directionality of electron beams in upward and downward direction, leading to type III bursts (of upward escaping electron beams), reverse-drifting decimetric bursts (of downward propagating electron beams), and correlated hard X-ray pulses (from directly precipitating electrons). Such triple-evidence of injected electron beams has been verified from radio dynamic spectra and correlated HXR pulses (Aschwanden et al. 1995b). Near the start frequency of upward propagating electron beams, some narrow-band spike bursts are occasionally detected at metric wavelengths, which are believed to be closest signatures of local acceleration processes (Benz 1994). VLA observations of such metric spikes indicate that they originate in relatively large coronal heights (Krucker et al. 1995). Upward escaping electron beams follow sometimes along large-scale arches, observable as metric type U-bursts with spatially widely-separated sources of the ascending and descending branches (Willson, Lang, and Gary 1993; Pick et al. 1994; Aurass & Klein 1996). Escaping electron beams have also been traced along collimated soft X-ray jets (Aurass, Klein, & Martens 1995; Raulin et al. 1995) or originating from flaring X-ray bright points (Kundu et al. 1995).

8.5. HIGH-ENERGETIC PARTICLES AND GAMMA RAYS

Some puzzling facts were observed in solar flare gamma rays. Gamma-rays of the 2.2 MeV neutron capture line, which is believed to be produced in the photosphere only, were observed from a 30^0 behind-the-limb flare (Vestrand & Forrest 1993). Extended gamma-ray emission was observed over periods of hours, up to a record of 8 hours (Kanbach et al. 1993), a fact that still puzzles experts whether long-term acceleration or trapping is at work (Ramaty & Mandzhavidze 1994). Abundance studies of flare-accelerated ions were found to imply that a larger fraction of the flare energy than previously believed is contained in accelerated ions (Ramaty et al. 1995). Gamma rays produced by electrons were observed up to several 100 MeV by GAMMA-1, while pion decay was found to dominate gamma-rays above 100 MeV (Akimov et al. 1994).

8.6. REVIEWS AND SUMMARIES

Recent reviews on the theory of particle acceleration processes can be found in Mandzhavidze & Ramaty (1993), Melrose (1994), Petrosian (1994), Mann (1994), Miller et al. (1996), and Ramaty, Mandzhavidze, & Hua (1996).

Reviews on observations of radio, hard X-ray and gamma-ray emission produced by non-thermal particles can be found in Lin (1993), Vilmer (1993), Trottet (1994), Chupp (1995), Hudson & Ryan (1995), Klein (1993; 1995), Simnett (1995), in Conference Proceedings edited by Gaizauskas & Machado 1994, Ryan & Vestrand (1994), Uchida et al. (1994), Ramaty, Mandzhavidze, & Hua (1996), in a monograph (Strong, Saba, & Haisch 1996), or textbook (Benz 1993).

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9. Solar Flares: 3-D Magnetic Field Modeling

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Flares obviously involve the evolution of 3-D magnetic configurations but the task to solve the associated MHD equations is such a formidable challenge that the problem has been traditionally reduced to 2-D. However, recently a major has been made in the understanding of the equilibrium configuration, stability, topology, energy build-up and release, as well in the opening conditions of 3-D magnetic configurations.

While there is presently no known 3-D analytical solutions of force free magnetic field equations, using a 2-D 1/2 analytical solution, Chou and Low (1994) describe the evolution, with emergence and shear, of a region formed by four photospheric field concentrations. The complexity of field line linkage, even in a simple 3-D configuration, is shown by Finn *et al.* (1994) with numerical solution of the linear force-free field equations. Such state can be formed by MHD relaxation to the Taylor-Heyvaerts-Priest state (Kusano *et al.*, 1994). McClymont and Mikić (1994) design a powerful method to compute the coronal magnetic field above active regions; it uses a 3-D resistive MHD code. They show that loops carrying enough electric current have a nearly constant cross-section as often observed by Yohkoh (see also van Hoven *et al.*, 1995). The stability analysis of 3-D line-tied configurations is usually tedious; Longbottom *et al.* (1993) and Hood *et al.* (1994) find simple estimates for the onset of ideal MHD instabilities.

Where is energy released in flaring configurations? For several confined flares, Bagalá *et al.* (1995), Démoulin *et al.* (1994b), Mandrini *et al.* (1993, 1995), van Driel-Gesztelyi *et al.* (1994) show that the Hα or UV brightenings are invariably located along sections of the computed separatrices and that they are linked in pairs by magnetic field-lines. This supports a reconnection model. In the same spirit, Parnell *et al.* (1994) interpret the X-ray loops of two bright points. The exploration of the rich variety of 3-D magnetic topologies has just begun. Separatrices and separators are present when either magnetic nulls (Lau, 1993) or field lines tangent to the photosphere are present (Titov *et al.*, 1993, Bungey *et al.*, 1996).

How energy is released? The classical view of 2-D magnetic reconnection at null points has been extended to 3-D. Two new classes of reconnection arise, called "spin" and "fan"; they are directly linked to the topology around a 3-D null point (Priest and Titov, 1996; Craig and Fabling, 1996). The sign of the vorticity in the inflow determines the reconnection rate (Jardine, 1994). However this may be only a partial view of the 3-D world! In the absence of magnetic nulls, as found by Démoulin *et al.* (1994a) in part of the flaring configurations studied, very thin current layers can still be formed (Longcope & Strauss, 1994b). 3-D reconnection may also occur at quasi-separatrix layers (QSLs) where there is a steep gradient in field-line linkage at the boundary (Priest and Démoulin, 1995; Démoulin *et al.*, 1996a,b). Finally in the absence of symmetry, Karpen *et al.* (1996) find that magnetic reconnection drives thin currents filamentation !

How and when the configuration get unstable? One possibility, explores further by Fushiki and Sakai (1995), Sakai *et al.* (1995), is the coalescence of two current loops. Another possibility is that photospheric motions drive the coronal field to marginal stability. It can be a coalescence instability (Longcope & Strauss 1994a, Longcope & Sudan, 1994) or a bifurcation of the equilibrium (Kusano *et al.*, 1995; Kusano and Nishikawa, 1996). Furthermore, eruptive flares are challenging because they imply an ejection of a part of the magnetic configuration. Both analytical (Lynden-Bell & Boily, 1994; Wolfson, 1995) and numerical simulations (Roumeliotis *et al.*, 1994; Sturrock *et al.*, 1995) show that an axisymmetric force-free field stressed by photospheric motions evolves with ideal MHD in two phases: a quasi-static and a dynamical one. In the last one, the field inflates tremendously, but without real loss of equilibrium, and it approaches the open field limit rapidly. The presence of a small resistivity allows the formation and ejection of a plasmoid (Mikić and Linker, 1994; Amari *et al.*, 1996a), the process being enhanced by solar wind (Mikić and Linker, 1995). All these results support Aly's conjecture (Aly, 1994, 1995 and references there in). Amari *et al.* (1996b) extend these results to true 3-D configurations, the main novelty being the partial opening of the field configuration after a finite shear.

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10. SOLAR FLARES: FLARE PLASMA

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In this report we will summarize the observational position following recent space-based observations along with the current state of theoretical understanding of the problem of high temperature solar plasma.

10.1. OBSERVATIONS

The Yohkoh Soft X-ray Telescope (SXT) has observed several hundred flares. As a flare develops, heated plasma is detected in associated active region magnetic loops - often in a single loop. Complimentary observations by the Bragg Crystal Spectrometer (BCS) confirm temperatures 2 - 25 MK, find non-thermally broadened emission lines (Khan et al. 1995; Mariska et al. 1996), and for events on the disc, show blue-shifted emission components. The latter indicate heated plasma moving upwards into the corona but the relative weakness of the blue component which is often observed suggests that not all of the plasma is produced from the chromosphere during the flare impulsive phase. The pre-impulsive phase occurrence of non-thermal line broadening suggests some in-situ heating following energy release in the

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In this report we will summarize the observational position following recent space-based observations along with the current state of theoretical understanding of the problem of high temperature solar plasma.

10.1. OBSERVATIONS

The Yohkoh Soft X-ray Telescope (SXT) has observed several hundred flares. As a flare develops, heated plasma is detected in associated active region magnetic loops - often in a single loop. Complimentary observations by the Bragg Crystal Spectrometer (BCS) confirm temperatures 2 - 25 MK, find non-thermally broadened emission lines (Khan et al. 1995; Mariska et al. 1996), and for events on the disc, show blue-shifted emission components. The latter indicate heated plasma moving upwards into the corona but the relative weakness of the blue component which is often observed suggests that not all of the plasma is produced from the chromosphere during the flare impulsive phase. The pre-impulsive phase occurrence of non-thermal line broadening suggests some in-situ heating following energy release in the corona. The early existence of heated coronal plasma can lead to *gentle evaporation* of chromospheric material following thermal conduction from the release site (Wulser et al. 1994). Occasionally violent chromospheric evaporation events, in which the blue-shifted emission component dominates the rest component during the impulsive phase, are observed (Culhane et al. 1994). An important observation by Hudson et al. 1994, used the SXT to register the occurrence of soft X-ray bursts at loop footpoints during the impulsive phases of several flares. These bursts accompanied the hard X-ray emission and suggest that non-thermal electron deposition heats the chromospheric plasma at the footpoints of flaring loops. For a much larger long-enduring event, Tsuneta (1996) has observed a flare which arises from a cusped helmet-like structure. The temperature of the subsequent loop X-ray emission is strongly suggestive of energy being supplied by continuing reconnection near the cusped loop top or by a downward propagating shock from the reconnection site. Feldman et al. (1994) have observed a number of flares for which the soft X-ray emission is concentrated in small loop-top volumes. They suggest that emission arises in a *pinched* plasma from which electrons are eventually accelerated down the loop legs. However, this observation may represent another manifestation of a high reconnection site with conduction in the loop suppressed by magnetic field topology. Although the existence of multiple flaring loops can lead to complex morphologies, Yohkoh observations with the Hard X-ray Telescope (HXT) generally indicate emission from two loop footpoints which correlate in time to within 100 ms (Sakao, 1994). However, Masuda et al. (1994) have discovered an impulsive hard X-ray source located above the soft X-ray flare loop in several compact events with the event of January 13, 1992, being particularly well studied. This source, which appears simultaneously with the usual double footpoint morphology and has a similar light-curve, may indicate the reconnection site or the interaction of a downward propagating shock with a reconnected post-flare loop. Non-thermal electrons accelerated in the interaction could heat the plasma and give rise to chromospheric evaporation. Aschwanden et al. (1996) have carried out a high-precision timing analysis of hard X-ray pulses in the 30-300 keV range with the Compton BATSE instrument and have established that observed energy-dependent time delays can be explained by electron time-of-flight differences. Comparison with Yohkoh images of the January 13, 1992, event reveal that the electron acceleration site was located a distance h above the loop top hard X-ray source where $h = 2.21 \pm 0.6 \times 10^4$ km. Work in progress by Aschwanden and colleagues indicates that this location is typical for a number of flares.

10.2. MODELS

Although the creation of high temperature plasma is mainly a consequence of the primary energy release and occurs on much larger spatial scales, understanding the heating mechanism is necessary for a complete understanding of energy release in the flare. While observations of emission line blue shifts clearly indicate upward motion of plasma, numerical modeling of electron beam heating of the chromosphere based on hydrodynamic codes has been unable to reproduce the observed time development and relative intensity of the blue-shifted component. It has been particularly difficult to explain observations of non-thermal line broadening and upward motion which can occur before the onset of the impulsive phase.

Further work on the DC-electric field model (Zarro et al. 1995) has enabled development of a flexible treatment of both plasma heating and electron acceleration depending on the electric field strength relative to a critical field value. Assuming a system of magnetic field-aligned currents and electric fields can be established in the flare loop, the high temperature plasma can be created by in-situ heating, by conduction-driven evaporation or by electron beam-driven evaporation with large values of electric field which cause runaway acceleration. The observation of hard X-ray loop-top sources by Yohkoh and the BATSE time-of-flight data suggest that the primary energy release site is located at an X-type neutral point above the loops which contain the heated plasma. The time-of-flight observations in particular require electron acceleration to take place above the hard X-ray source. Wheatland and Melrose (1995) have proposed a model consistent with this in which down-streaming electrons produce the hard X-ray emission through partial trapping in the region above the plasma loop followed by precipitation at the loop footpoints. On the other hand Tsuneta (1995) favors a model in which the interaction of a fast outflow from the reconnection site with the reconnected loop leads to charge separation and the generation of field-aligned currents within the loop by DC electric fields. This approach can explain the observed plasma heating phenomena as described above but is difficult to reconcile with the hard X-ray timing data. While the observations now seem to favor reconnection at a neutral point above the flare loop as the energy release mechanism for both large and compact flares, the explanation of the nature and location of the electron acceleration mechanism requires further clarification of the hard X-ray spatial and timing data.

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11. THE ACTIVE CORONA OBSERVED FROM SPACE: JETS AND TRANSIENT BRIGHTENINGS

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11.1. X-RAY JETS

X-ray jets have been discovered by the soft X-ray telescope aboard *Yohkoh* as transitory X-ray enhancements with apparent collimated motion (Strong et al. 1992). They are associated with micro-flares or subflares,which occurred in X-ray bright points (XBPs), emerging flux regions, and active regions. According to statistical study of 100 jets by Shimojo et al. (1996), the length of the jets is $10^3 - 4 \times 10^5$ km (average $\simeq 1.5 \times 10^5$ km), the apparent velocity is $10 - 1000$ km/s (average $\simeq 200$ km/s), and the lifetime ranges from a few minutes to more than a few hours. The number of jets decreases as the length, the velocity, or the lifetime increases, and histograms are similar to those of flares and EUV explosive events. The temperature of jets ($\sim 3 - 6$ MK) is comparable to that of micro-flares at the footpoints of the jets, and the kinetic energy is estimated to be $10^{25} - 10^{28}$ erg. Shimojo et al. (1996) found that the width of the jets often decreases with height (i.e., *converging* shape), which is similar to the shape of Hα surges observed in emerging flux regions (Kurokawa and Kawai 1993) and EUV macrospicules (Karovska and Habbal 1994).

There are many evidences of magnetic reconnection in jets (Shibata et al. 1994a,b, 1996); i.e., change of magnetic field topology at the footpoint active regions, and so on. Shibata et al. (1994b) found two types of the interaction (reconnection) between emerging flux and coronal field; the *anemone-jet* type and the *two-sided-loops-jets* type. The former occurs when emerging flux appears in coronal holes. In this case, a jet is ejected in a vertical direction. On the other hand, the latter occurs when emerging flux appears in quiet regions, and two loop brightenings (or jets) occur in the horizontal direction at both sides of the emerging flux.

Yokoyama and Shibata (1994, 1995, 1996) successfully modeled these two types of reconnection of emerging flux with pre-existing magnetic fields, by performing 2-D MHD numerical simulations. (See Matsumoto et al. 1993 for a 3-D model of emerging flux.) In these models, the reconnection produces not only hot jets (X-ray jets) but also hot loops ($\sim$ *transient brightenings*; Shimizu et al. 1992) and even cool jets. The cool jets possibly correspond to Hα surges that are often associated with X-ray jets (Canfield et al. 1996). Priest et al. (1994) and Parnel et al. (1994) presented a slightly different reconnection model (i.e., "converging flux" model) for X-ray bright points and jets. Though these reconnection models are successful as energy release mechanism, the specific acceleration mechanism of each jet remains to be identified; in fact, there is a possibility that some of jets are evaporation flow accelerated by thermal pressure force (e.g., Sterling et al. 1993) even if reconnection is the energy release mechanism.

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12. THE ACTIVE CORONA OBSERVED FROM SPACE: LARGE-SCALE EVOLVING STRUCTURES

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12.1. INTRODUCTION

Series of new discoveries on large-scale coronal structures have been made so far with *Yohkoh* since its launch in August, 1991: the global structural changes of soft X-ray structures, especially the formation of spectacular arcades, X-ray jets (Shibata et al. 1994), and interacting active regions (Tsuneta 1996a) in static large-scale X-ray corona outside active regions. Although the transient nature of the solar corona was noticed earlier by *Skylab* observers the extent of its time variability has been fully appreciated with the advent of *Yohkoh*. One is also beginning to realize that all these transient phenomena are due to magnetic reconnection. Here, "transient" means that the observed time-scale roughly ranges between 10 and 100 Alfvén transit times of the system. The time-scale of the transient events tends to be shorter in active regions, and longer for large-scale events in the quiet Sun. However, if one normalizes the time-scale with Alfvén transit time, the time-scale is almost invariant (Tsuneta 1996c).

12.2. FORMATION OF LARGE SCALE ARCADE

Yohkoh X-ray movies show that even the quiet Sun often has large-scale structural changes as well as brightenings (heating). The number of these transient events appears to decrease from the solar maximum to the minimum. One type of transient events are the large-scale arcades (Hanaoka et al. 1994, Hiei, Hundhausen, & Sime 1993), which appear to be associated with the global eruption of coronal magnetic structures in X-rays together with prominence eruption. The eruptive structures are also observed as coronal mass ejection (CME; McAllister et al 1996, McAllister, & Hundhausen 1996). As a result of the eruption, the neutral sheet structure is dynamically formed, and magnetic reconnection takes place (Magara et al. 1996, Yokoyama & Shibata 1996). The reconnected field lines are heated, and resultant chromospheric evaporation increases a plasma density of the flux tubes. This makes the reconnected loop structure highly visible in soft X-rays. When an arcade is formed near the limb, a distint triangular structure, which we call "cusp" structure, is seen (Tsuneta et al. 1992a). The cusp structure suggests the X-point structure located above the arcade (reconnected loops).

These cusp structures are seen also in flares, especially in the Long Duration Events (LDE;Tsuneta 1996), as well as in active regions (Yoshida & Tsuneta 1996). The cusps seen in active regions are as small as 10^4 km. The giant cusps with size as large as solar radius in the quiet Sun, the cusps seen in LDE flares, and the mini-cusps in active regions are apparently governed by the same physical process; magnetic reconnection.

12.3. WHAT DRIVES THE GLOBAL ERUPTION?

It is not yet understood how eruption occurs, what drives eruption, and how the X-type neutral point structure is formed as a result of eruption. There are ubiquitous neutral sheet structures with size as small as 10^3 km to the size as large as the solar radius in the quiet Sun. These neutral sheet structures appear to be static, or dormant, and do not have transient magnetic reconnection. Only the dynamically-formed neutral sheet structures in association with global eruption, have magnetic reconnection.

Since the eruption and subsequent formation of the cusp structure occur both in active regions, and in the quiet Sun, the cusp formation appears to be scale-invariant. Many authors try to understand the eruption as driven by the photospheric shear motion. This may not be consistent with the following two facts (Tsuneta 1996): (1) such photospheric motion should also have had scale-invariant nature from 10^3 km to the size comparable to solar radius. (2) The number of cusp events decreases with lower solar activity from 1991 to 1996. This indicates that the photospheric shear motion should have also significantly been affected by the solar cycle.

12.4. LARGE-SCALE ERUPTION AND CME

The eruptions observed with *Yohkoh* probably evolve to the larger scale eruptions observed as CME. From Yohkoh observations, it is clear that the eruption (CME) is not a result of the transient events including solar flares. It is rather related to the cause of the formation of large-scale arcade. These new observations are quite consistent with the viewpoint by Gosling (1993), Hudson, Haisch, & Strong (1995), and Hundhausen (1996).

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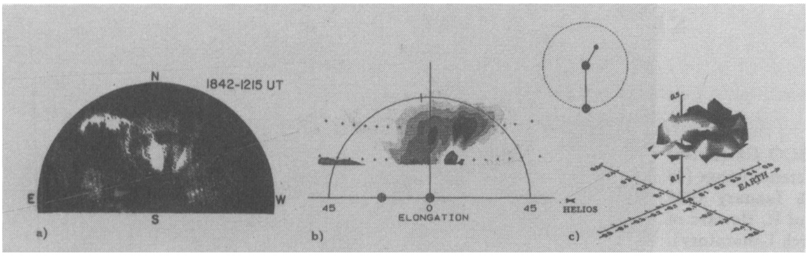

Figure 1. **24 May 1979 CME a) Solwind image. b) Helios image. c) 3-D reconstruction.**

13. THE ACTIVE CORONA OBSERVED FROM SPACE: CORONAL MASS EJECTIONS

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13.1. INTRODUCTION

Observed as outward motions of mass through the solar corona, coronal mass ejections (or CMEs) are some of the most energetic solar events known. CMEs are now understood to be formed by the magnetic/current processes responsible for other strong magnetic field solar phenomena such as sunspots. Current analyses indicate that CMEs comprise a substantial portion of the solar wind, especially at times of solar maximum.

13.2. REPRESENTATIVE DATA

Several thousand CMEs have now been imaged by the Solwind and SMM coronagraphs and, using similar Thomson-scattering observations, from the photometers on board the Helios spacecraft. Information about polar CMEs, free of interactions with dense, slower structures present at lower heliographic latitudes, has become available recently from Ulysses spacecraft observations *in situ* (Gosling *et al.*, 1995). Figure 1a is an example from the Solwind coronagraph, where a pre-event CME image has been subtracted from one containing the event in order to display excess brightness from the outward-moving material. A Helios photometer image of the same CME is shown in Figure 1b, but viewed from the opposite side of the Sun.

13.3. RECENT ANALYSES

Recent analyses using coronagraph images show that CMEs provide a significant portion of the solar wind mass ($\geq$15%) outflow (Jackson and Howard, 1993) at solar maximum (Webb and Howard, 1994), and that small mass CMEs are limited in number. This conclusion is confirmed by the Helios photometer CME observations which indicate that actual CME masses derived from Helios data are on average three times larger than masses derived from coronagraph data (Webb *et al.*, 1996).

While these events can spread over a significant volume of space (Hundhausen *et al.*, 1993), they none-the-less concentrate a great deal of mass and energy into a relatively small volume of the solar wind (Jackson, 1996) centered on the solar equator. It is for these reasons that CMEs are considered to be the key causal link between solar activity and major transient interplanetary and geomagnetic activity (*e.g.*, Tsurutani *et al.*, 1993).

It is difficult to observe CMEs among the many other types of solar activity present in *e.g.*, *Yohkoh* solar X-ray telescope (SXT) images of the low corona ($\leq 1.15 R_S$). The manifestations of CMEs in these observations are often mass depletions (Hudson, 1996) indicating that CMEs originate from large structures at or beyond this inner coronal region. Others, including (*e.g.*, Hundhausen, 1996) have recently noted that the brightnesses of solar flares are not well-correlated with CMEs, and this has lead to a great deal of recent discussion about the possibility of a solar flare 'myth' (following Gosling, 1993).

and timing data.

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11.1. X-RAY JETS

X-ray jets have been discovered by the soft X-ray telescope aboard *Yohkoh* as transitory X-ray enhancements with apparent collimated motion (Strong et al. 1992). They are associated with micro-flares or subflares,which occurred in X-ray bright points (XBPs), emerging flux regions, and active regions. According to statistical study of 100 jets by Shimojo et al. (1996), the length of the jets is $10^3 - 4 \times 10^5$ km (average $\simeq 1.5 \times 10^5$ km), the apparent velocity is $10 - 1000$ km/s (average $\simeq 200$ km/s), and the lifetime ranges from a few minutes to more than a few hours. The number of jets decreases as the length, the velocity, or the lifetime increases, and histograms are similar to those of flares and EUV explosive events. The temperature of jets ($\sim 3 - 6$ MK) is comparable to that of micro-flares at the footpoints of the jets, and the kinetic energy is estimated to be $10^{25} - 10^{28}$ erg. Shimojo et al. (1996) found that the width of the jets often decreases with height (i.e., *converging* shape), which is similar to the shape of Hα surges observed in emerging flux regions (Kurokawa and Kawai 1993) and EUV macrospicules (Karovska and Habbal 1994).

There are many evidences of magnetic reconnection in jets (Shibata et al. 1994a,b, 1996); i.e., change of magnetic field topology at the footpoint active regions, and so on. Shibata et al. (1994b) found two types of the interaction (reconnection) between emerging flux and coronal field; the *anemone-jet* type and the *two-sided-loops-jets* type. The former occurs when emerging flux appears in coronal holes. In this case, a jet is ejected in a vertical direction. On the other hand, the latter occurs when emerging flux appears in quiet regions, and two loop brightenings (or jets) occur in the horizontal direction at both sides of the emerging flux.

Yokoyama and Shibata (1994, 1995, 1996) successfully modeled these two types of reconnection of emerging flux with pre-existing magnetic fields, by performing 2-D MHD numerical simulations. (See Matsumoto et al. 1993 for a 3-D model of emerging flux.) In these models, the reconnection produces not only hot jets (X-ray jets) but also hot loops ($\sim$ *transient brightenings*; Shimizu et al. 1992) and even cool jets. The cool jets possibly correspond to Hα surges that are often associated with X-ray jets (Canfield et al. 1996). Priest et al. (1994) and Parnel et al. (1994) presented a slightly different reconnection model (i.e., "converging flux" model) for X-ray bright points and jets. Though these reconnection models are successful as energy release mechanism, the specific acceleration mechanism of each jet remains to be identified; in fact, there is a possibility that some of jets are evaporation flow accelerated by thermal pressure force (e.g., Sterling et al. 1993) even if reconnection is the energy release mechanism.

Canfield et al. (1996) found several examples of simultaneous ejection of X-ray jets and Hα surges in the same direction. These surges are known to spin around their axis. (Note that there are also many Hα surges which are not associated with X-ray jets; e.g., Schmieder et al. 1995). Kundu et al. (1995) found that a type III burst was associated with an X-ray jet (see also Auras et al. 1995, Raulin et al. 1996). This implies the existence of high energy electrons in these small flares and jets, and supports the view that the generation mechanism of X-ray jets and micro-flares may be physically similar to that for larger flares.

It is interesting to note that Shibata et al. (1995) discovered X-ray plasma ejections (some are similar to jets) even from the impulsive compact loop flares, e.g., the Masuda (1994) flare, which have been considered to be *confined*. Based on this finding, Shibata (1996) presented a unified model to explain LDE flares, impulsive flares, and micro-flares/jets with a single physical mechanism, magnetic reconnection triggered by plasmoid ejection.

11.2. TRANSIENT BRIGHTENINGS

The soft X-ray telescope aboard *Yohkoh* found another interesting phenomenon, i.e., *transient brightenings*, which frequently occur in "active" active regions (Shimizu et al. 1992). According to Shimizu et al. (1992), the *active region transient brightenings* (ARTBs) usually show a single or multiple loops, the total thermal energy content in one transient brightening is $10^{25} - 10^{29}$ erg, time scale $1 - 10$ min, and the loop length is $0.5 - 4 \times 10^4$ km. They further found that ARTBs correlate well with GOES C-class or sub-C-class flares so that ARTBs are considered to be a spatially resolved soft X-ray counterpart of hard X-ray micro-flares. Morphology of ARTBs, such as multiple loop structures (e.g. Hanaoka 1996), is suggestive of *loop-loop interaction* or *two current loop interaction* (e.g., Fushiki and Sakai 1995), though clear evidence of *interaction* between *two current loops* has not yet been found.

From simultaneous observations by VLA and *Yohkoh*, Gopalswamy et al. (1994) found microwave counterparts of ARTBs. White et al. (1995) reported that no impulsive radio emission at 17 GHz was detected from ARTBs, using the Nobeyama Radioheliograph. This negative result leaves open the possibility that there is a difference between ARTBs and large flares. On the other hand, Kundu et al. (1994) observed type III bursts in association with an XBP flare, which means that XBP flares are similar to normal flares and can accelerate non-thermal electrons.

Shimizu (1995) found that the number of ARTBs, N, as a function of their total thermal energy content, W, scales as a single power law; $dN/dW \propto W^{-(1.55\pm0.05)}$, where W ranges from 10^{27} to 10^{29} erg. Since this relation is essentially the same as that of larger flares, it is likely that the same physical mechanism causes ARTBs as in larger flares. On the other hand, this means that the coronal heating cannot be explained by X-ray micro-flares, since the power law index is less than the critical value 2. However, Porter et al. (1994) claimed that EUV micro-flares show the power law index larger than 2. Yokoyama and Shibata (1995) pointed out that the jets are often associated with micro-flares, while the kinetic energy of the jets has not been considered in the estimate of energy. The inclusion of the kinetic energy would change the power law index significantly.

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12. THE ACTIVE CORONA OBSERVED FROM SPACE: LARGE-SCALE EVOLVING STRUCTURES

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12.1. INTRODUCTION

Series of new discoveries on large-scale coronal structures have been made so far with *Yohkoh* since its launch in August, 1991: the global structural changes of soft X-ray structures, especially the formation of spectacular arcades, X-ray jets (Shibata et al. 1994), and interacting active regions (Tsuneta 1996a) in static large-scale X-ray corona outside active regions. Although the transient nature of the solar corona was noticed earlier by *Skylab* observers the extent of its time variability has been fully appreciated with the advent of *Yohkoh*. One is also beginning to realize that all these transient phenomena are due to magnetic reconnection. Here, "transient" means that the observed time-scale roughly ranges between 10 and 100 Alfvén transit times of the system. The time-scale of the transient events tends to be shorter in active regions, and longer for large-scale events in the quiet Sun. However, if one normalizes the time-scale with Alfvén transit time, the time-scale is almost invariant (Tsuneta 1996c).

12.2. FORMATION OF LARGE SCALE ARCADE

Yohkoh X-ray movies show that even the quiet Sun often has large-scale structural changes as well as brightenings (heating). The number of these transient events appears to decrease from the solar maximum to the minimum. One type of transient events are the large-scale arcades (Hanaoka et al. 1994, Hiei, Hundhausen, & Sime 1993), which appear to be associated with the global eruption of coronal magnetic structures in X-rays together with prominence eruption. The eruptive structures are also observed as coronal mass ejection (CME; McAllister et al 1996, McAllister, & Hundhausen 1996). As a result of the eruption, the neutral sheet structure is dynamically formed, and magnetic reconnection takes place (Magara et al. 1996, Yokoyama & Shibata 1996). The reconnected field lines are heated, and resultant chromospheric evaporation increases a plasma density of the flux tubes. This makes the reconnected loop structure highly visible in soft X-rays. When an arcade is formed near the limb, a distint triangular structure, which we call "cusp" structure, is seen (Tsuneta et al. 1992a). The cusp structure suggests the X-point structure located above the arcade (reconnected loops).

These cusp structures are seen also in flares, especially in the Long Duration Events (LDE;Tsuneta 1996), as well as in active regions (Yoshida & Tsuneta 1996). The cusps seen in active regions are as small as 10^4 km. The giant cusps with size as large as solar radius in the quiet Sun, the cusps seen in LDE flares, and the mini-cusps in active regions are apparently governed by the same physical process; magnetic reconnection.

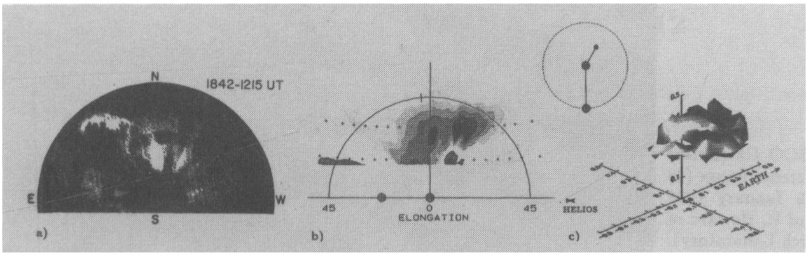

Figure 1. 24 May 1979 CME a) Solwind image. b) Helios image. c) 3-D reconstruction.

13. The Active Corona Observed from Space: Coronal Mass Ejections

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13.1. INTRODUCTION

Observed as outward motions of mass through the solar corona, coronal mass ejections (or CMEs) are some of the most energetic solar events known. CMEs are now understood to be formed by the magnetic/current processes responsible for other strong magnetic field solar phenomena such as sunspots. Current analyses indicate that CMEs comprise a substantial portion of the solar wind, especially at times of solar maximum.

13.2. REPRESENTATIVE DATA

Several thousand CMEs have now been imaged by the Solwind and SMM coronagraphs and, using similar Thomson-scattering observations, from the photometers on board the Helios spacecraft. Information about polar CMEs, free of interactions with dense, slower structures present at lower heliographic latitudes, has become available recently from Ulysses spacecraft observations *in situ* (Gosling *et al.*, 1995). Figure 1a is an example from the Solwind coronagraph, where a pre-event CME image has been subtracted from one containing the event in order to display excess brightness from the outward-moving material. A Helios photometer image of the same CME is shown in Figure 1b, but viewed from the opposite side of the Sun.

13.3. RECENT ANALYSES

Recent analyses using coronagraph images show that CMEs provide a significant portion of the solar wind mass ($\geq$15%) outflow (Jackson and Howard, 1993) at solar maximum (Webb and Howard, 1994), and that small mass CMEs are limited in number. This conclusion is confirmed by the Helios photometer CME observations which indicate that actual CME masses derived from Helios data are on average three times larger than masses derived from coronagraph data (Webb *et al.*, 1996).

While these events can spread over a significant volume of space (Hundhausen *et al.*, 1993), they none-the-less concentrate a great deal of mass and energy into a relatively small volume of the solar wind (Jackson, 1996) centered on the solar equator. It is for these reasons that CMEs are considered to be the key causal link between solar activity and major transient interplanetary and geomagnetic activity (*e.g.*, Tsurutani *et al.*, 1993).

It is difficult to observe CMEs among the many other types of solar activity present in *e.g.*, *Yohkoh* solar X-ray telescope (SXT) images of the low corona ($\leq 1.15 R_S$). The manifestations of CMEs in these observations are often mass depletions (Hudson, 1996) indicating that CMEs originate from large structures at or beyond this inner coronal region. Others, including (*e.g.*, Hundhausen, 1996) have recently noted that the brightnesses of solar flares are not well-correlated with CMEs, and this has lead to a great deal of recent discussion about the possibility of a solar flare 'myth' (following Gosling, 1993).

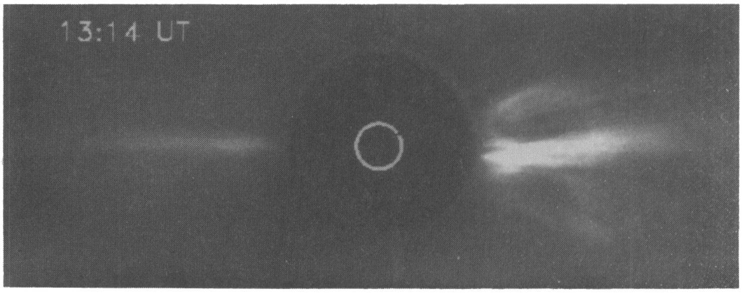

Figure 2. LASCO C3 (outer) coronagraph difference image (to $15R_S$) of the 15 January 1996 CME (courtesy of R. Howard of the Naval Research Laboratory).

Recent progress in the determination of CME three-dimensional structure from tomographic techniques using multiple perspective views of CMEs (Jackson and Froehling, 1995) is presented in Figure 1c. While these analyses are restricted to low resolution by the assumptions inherent in the technique, they show that CMEs are extensive heliospheric structures.

13.4. CONCLUSIONS

A new, exciting phase in CME studies has begun with the exquisitely detailed CME observations obtained by the recently-launched SOHO LASCO coronagraphs (Brueckner *et al.*, 1995) (Figure 2) which can view CME outward motion from $0.1R_S$ to $\sim 30R_S$. It is possible that these images will allow determination of the energy processes driving CMEs outward and their relation to the global solar current system from which they originate.

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