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VII. Active Regions: Structure and Evolution
(V. Gaizauskas)

The corona above active regions is now recognized as an assemblage of magnetically confined loops of plasma. This advance in understanding the active upper atmosphere is documented in the monograph resulting from the Third Skylab Workshop (Solar Active Regions, 1981, ed., F.Q. Orrall). International collaborative programs during the Solar Maximum Year (SMY) have further stimulated the study of active regions with emphasis on the search for the underlying causes of solar flares. Scores of analyses of individual regions, combining space- and ground-based observations, have been published. We have as a result an improved picture of interactions between active regions: from creation of shear in the magnetic topology to inter-region connections via the corona. A revived interest in the phenomena of recurrent active regions and sunspot decay has highlighted a basic problem for solar magnetism: the removal of magnetic flux from the solar surface. The interpretation of temporary dips in the solar irradiance caused by active regions continues to generate lively debate.

A. SMALL-SCALE MAGNETIC FIELDS

Recent developments in measuring the fine-scale magnetic structure, with stress on the problems of interpreting those measurements, are reviewed by Stenflo (1984a,b,c). A major advance is the simultaneous recording of fully resolved, circularly polarized spectra of hundreds of spectral lines with the Fourier Transform Spectrometer at the McMath Telescope (Stenflo et al. 1984). Plasma diagnostics can thus be derived over a wide range of excitation conditions. In comparing plage and network areas with this technique, Solanki & Stenflo (1984) confirm that their magnetic field strengths are approximately equal; they find similar velocity structures in plage and network, but network flux tubes are hotter in their lower layers as compared to plages. If there is a chaotic field between the intermittent strong field elements, Stenflo (1982) can put a lower limit on it of 10 Gauss from a first attempt to measure the depolarization of scattered radiation on the fringe of active regions by the Hanle effect. The speed and sensitivity gained by integrating videomagnetograms make it possible to follow interactions between fine-scale fragments of solar magnetic fields (Martin 1984). When like polarities collide, they merge without obvious change in net magnetic flux; when fragments of opposite polarities collide, there is a gradual loss of flux in both fragments until the smaller one disappears. It is not clear whether the loss of flux occurs through reconnection or submergence of flux loops. Wilson & Simon (1983) found large and rapid fluctuations in small unipolar magnetic features with no observable changes in the fragments of strong fields in the opposite polarity. Daras-Papamargaritas & Koutchmy (1983) have measured the magnetic flux in a "rosette" ($\approx 10^{20}$ Mx) and estimate a flux of 5×10^{18} Mx per Hα fibril. The anti-correlation between coronal bright points and sunspot number has been confirmed (Davis 1983); the lack of direct correspondence between bright points and ephemeral regions (Tang et al. 1983) remains enigmatic. A solar cycle dependence is indicated for the density of photospheric network elements (Müller & Roudier 1984) and of chromospheric granules (Fang et al. 1984).

B. GROWTH AND DISAPPEARANCE

Observations at high spatial and spectral resolution (Zwaan et al. 1984, Brants 1985) reveal that a new pore strengthens by adding new flux at the edge facing the center of its growing region; the rule that an emerging flux region grows outward from its center extends right to its birth. Garcia de la Rosa

(1983, 1984) finds intrinsic differences between small and large ($\approx 5 \times 10^{22}$ Mx) regions which he attributes to different depths and modes of birth: as loosely packed flux tubes submerged among the supergranules for the small ones; as tightly wound flux ropes at the bottom of the convection zone for the large ones; Parker (1984a) estimated the depth of origin quantitatively by assuming that regions disappear by being pulled back into the Sun and that surface fields are controlled at unique subsurface anchor points. Evidence which can be interpreted as submerging flux (Rabin & Moore 1984) keeps mounting, although conclusive evidence has never been reported, such as reversal of the normal spreading of a bipolar pair. In his review of extensive observations at Ondrejov on the motions and changes in shapes of evolving sunspots, Bumba (1983) cites patterns of development which he cannot reconcile with the concept of emerging flux. Akasofu (1984) is developing a model in which hydrodynamic forces act on the large-scale background magnetic fields at the surface to create a photospheric dynamo. The term "naked sunspot" was coined by Ligget & Zirin (1983) to describe aged, large sunspots without accompanying plage. The plage-associated fields are presumed to disappear first through local reconnections in the large unipolar areas which such spots prefer. Because these spots disappear without trace, the remnant dispersed fields of active regions are likely left by dissolving plages, not by sunspots. Active regions do not form at random over the Sun. Ligget & Zirin (1984) measured a rate of flux emergence 27 times higher within active regions than in quiet background areas at the same latitudes. Active regions cluster in space and time in distinct entities called "complexes of activity"; yet flux does not accumulate in a complex (Gaizauskas et al. 1983). Flux disappears locally at a rate which balances the rate of emergence in the same complex. Each complex rotates around the Sun with its own period. At times complexes are spaced regularly around the active belts of latitude in bands of alternating polarity. Parker (1984a) shows that the gaps between complexes should block reconnection and prevent the escape of any substantial amounts of flux by this process. Loss of flux from the solar surface remains a more subtle problem than imagined; its resolution has profound consequences for concepts of the solar dynamo.

C. CORONAL INTERCONNECTIONS

Coronal loops track active region evolution; new loops connect with older sets as new active regions appear (Sheeley 1981). The transient brightenings observed in these interconnecting loops are interpreted by Spicer & Švestka (1983) as due to either excitation of the fast tearing mode in young, newly born loops or possibly to anomalous Joule heating in the old loop connections. Hot plasma ($\approx 10^7$ K) above active regions has been found even in the absence of flares (Schadee et al. 1983). The character of faint x-ray (≈ 3.5 keV) emission depends upon the stage of the region's development. Interconnection of widely spaced, non-flaring active regions has also been observed (Farnik & van Beek 1984). Large-scale C IV velocity patterns have been found in close correspondence with photospheric magnetic fields in active regions: over sunspots it is in the reverse Evershed sense with a substantial vertical component (Athay et al. 1982); outside of sunspots it is nearly horizontal with a preference for downflow (≈ 10 km/s) in both legs of flat loops (Athay et al. 1983). Systems of C IV loops last many hours over active regions, often rising into the corona. A geometrical technique for reconstructing the true shapes of solar loops observed on the disk is described in a series of papers: Loughhead et al. (1983a), Chen & Loughhead (1983), Wang et al. (1984), Loughhead et al. (1984). During a subflare observed at 6 cm and in Hα (Kundu et al. 1983), simultaneous brightenings at both wavelengths were observed $\approx 10^5$ km away from the primary site of energy release. Using co-temporal microwave (1.8 cm, spatially resolved) and hard x-ray (HXRBS) observations, Nakajima et al. (1985) found transient events with secondary microwave bursts 10^5-10^6 km away from the primary sites of energy release. The distant bursts could be produced by electron beams with energies 10-100 keV channeled along a connecting loop; two of these events had "sympathetic" flares triggered at remote sites. Simultaneous eruptions are reported in many studies:

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between adjacent active regions (Golovko et al. 1981, Gaizauskas 1983, Loughhead et al. 1983b, Machado et al. 1983); between widely spaced regions (Ogir 1981); and even as coronal transients on opposite limbs (Wagner & Wagner 1984). Stresses built up by the normal evolution of active regions are sensed by the global network of coronal loops; their release is complicated by this interdependence. If sites of energy storage do exist, they need not coincide with the sites of initial energy release.

D. FLARE-ASSOCIATED EVOLUTION

The source of flare energy is believed to be the free energy stored in magnetic fields stressed by evolutionary trends in active regions, i.e., by emergence of additional flux and by proper motions of sunspots (Priest 1984a,b). The elucidation of these trends is the goal of the Flare Build-Up Study. Many accounts illustrate increased flare activity in locations of sheared magnetic and velocity fields: Krall et al. (1982), Nagy (1983), Kalman & Nagy (1983), Kalman (1984), Dezsö et al. (1984), Zirin (1983, 1984). An MHD model of sheared loops by Wu et al. (1984) shows a growth rate roughly proportional to the shearing speed and a buildup of magnetic energy near the neutral lines. Calculations of magnetic shears (Hagyard et al. 1984) and of current densities (Gopasryuk et al. 1983) for observed active regions show that flares occur where continued magnetic evolution of the region push these parameters to critical values. In their study of the development of shear, Athay et al. (1985a) found very little flare activity despite sustained strong shear along a magnetic neutral line, except for minor disruptions associated with emerging flux. The strongly flare productive δ-regions (Knoska & Krivsky 1983) often form by collision of neighboring, growing bipolar regions (Tang 1983, Gesztelyi & Kondas 1983, Gesztelyi 1984). Athay et al. (1985b) followed a growing δ-region from a state of weak to a state of strong magnetic shear in localized zones. Although large flares occurred in some strongly sheared zones, none occurred in other zones of strong shear in the same region. Magnetic shear alone is not sufficient to produce large flares. The role of magnetic flux is ambivalent. Emergence of a bipole is accompanied by lateral spreading which can lead to complex interactions with pre-existing fields either nearby or at remote locations. Although emerging flux is closely associated with small flares inside an EFR (Martin 1983) and is often invoked as a trigger for larger flares (Moore et al. 1984, Simon et al. 1985), there are also clear examples of flares with strong filament eruptions and no emerging flux (Gaizauskas 1984).

E. RADIO EMISSION

The rapid progress toward an understanding of the emission processes in coronal structures above active regions has been greatly stimulated by the application of supersynthesis arrays to solar observations (see review by Kundu 1982). The bipolar character of magnetic fields above active regions is the dominant factor in shaping and insulating structures in the multi-thermal coronal plasma (Dulk & Gary 1983, Lang & Willson 1983). The model-dependent identification of emission processes becomes more problematic at the shorter wavelengths which originate at lower levels near regions of intense fields. A new thermal model incorporating a force-free field extrapolation has been developed by Staude et al. (1983) and applied to observations by Urpo et al. (1982), Seehafer et al. (1983), Kaverin et al. (1983), Akhmedov et al. (1983), and Hildebrandt et al. (1984). A new model by Alissandrakis & Kundu (1984) has been applied to the center-to-limb variation of a pair of large active regions. A non-thermal model has been proposed by Chiuderi-Drago & Melozzi (1984) to account for high temperature radio sources uncorrelated with sunspots or x-ray sources. Bandiera (1982) has developed a diagnostic for deducing magnetic fields above bipolar regions which needs no assumptions about the emission mechanism. The structures of radio sources and their associations with x-ray and optical structures are so complex (Webb et al. 1983) that little can be offered as yet by way of simplification. Other multi-wavelength observations confirm the conclusion of Webb et al. that the presence of a strong magnetic field is not a sufficient condition for bright microwave emission; they further show that the 20-cm emission is the microwave thermal counterpart of soft x-ray emission from large loops straddling a bipolar region, while the 6-cm emission is attributed to gyro-resonant emission, usually from the legs of loops associated with sunspots, but also from arcades of loops in locations of strong transverse magnetic fields (Lang et al. 1983, McConnell & Kundu 1983, 1984, Shibasaki et al. 1983, Strong et al. 1984, Kundu & Alissandrakis 1984). The bewildering profusion of radio sources with very different structures suggests that clarifying knowledge of the long-term evolution of microwave emission from a single active region observed at high spatial resolution is needed. A three-dimensional structure for a large coronal loop over an active region has been presented by Shevgaonkar & Kundu (1984). Schmahl et al. (1984) have mapped a region with an anomalously high spectral index which they explain in terms of emission in cyclotron lines. Brueckner (1983) found that all Type I noise storms observed during the Skylab period were caused by changes in coronal magnetic field structure; all disk changes were correlated with emerging flux.

F. VARIABILITY IN SOLAR IRRADIANCE

The blocking by active regions of heat transported from the convection zone continues to stir debate. The background and future directions of this topic are summarized in reviews by Newkirk (1983) and Willson (1984) and in the proceedings of the Caltech Workshop on Solar Irradiance Variations on Active Region Time Scales. Opinion is sharply divided between two alternatives: either the blocked enrgy is stored in the convection zone for long periods of time (Foukal et al. 1983) or it is re-routed and quickly re-radiated by faculae (Oster et al. 1982, Chapman et al. 1984). The former alternative leads to a solar luminosity modulated weakly at the 11-year period of the solar cycle, while the latter accounts only for daily changes in solar irradiance. Tests to resolve this issue by appealing to archival records are as yet inconclusive (Eddy 1984). Much of the dispute arises from the poor quality of information about faculae, particularly about their role in the evolution of active regions. Attempts to solve the controversy will remain speculative until a prolonged data base is available from irradiance monitors with modern detectors (Hudson et al. 1984). Fowler et al. (1983) find marginally significant bright rings of non-facular origin around sunspots, much weaker than predicted from conventional mixing-length theory; significantly lower values of the eddy thermal conductivity are indicated. An upper limit of 1.5 K rms can be placed on any thermal shadow over the area occupied by an active region 1 day before it appears (Foukal 1984). The growth and breakup of plages measured during the solar cycle seem insufficient to account for the cycle-dependent increase of Ca K emission which has been modeled by Skumanich et al. (1984). The effect on solar UV irradiance by the evolution of active regions has been determined by Donnelly et al. (1982); UV variability cannot be neglected in determining the facular contribution to the total irradiance (Donnelly et al. 1984).

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VIII. Theory of Flares

(E.R. Priest)

Magnetohydrodynamic (MHD) theory for the initiation and development of solar flares has developed considerably over the past 3 years and represents one of the liveliest areas of solar physics (Hood & Priest, 1981a, Priest 1983a,b, Schindler 1982, Van Hoven 1982, Syrovatskii et al. 1983). This has been stimulated by a thorough analysis of the Skylab observations and also by the startling new observations from the Solar Maximum Mission (SMM). In addition, the realization that flares appear to form two basic types, namely, small simple-loop flares and large two-ribbon flares, has focussed the imagination of theorists (e.g., Priest 1981, 1982), even though reality may be somewhat more complex. In the former type, a single-loop structure brightens up and decays without moving; whereas in the latter, an active region filament erupts and then two ribbons of chromospheric emission form and separate, with an arcade of hot and cool loops joining them.

The basic theory for hydrodynamic flow in a rigid loop and for magnetic field reconnection has been studied in depth, as summarized below. Major theoretical problems have been to try and understand how the magnetic field can become unstable and so initiate a flare in the two basic geometries, namely, a loop and an arcade. Also, the creation of post-flare loops by magnetic reconnection as the magnetic field closes back down in the main phase of a two-ribbon event has been modeled, and the roles of emerging flux are being clarified.

All these are at present active topics and one expects much theoretical progress over the next few years. In particular, the coupling of loop flow to the magnetic field should be studied, and the details of the new fast reconnection regions and of the nonlinear development of tearing should be worked out. Coupling the MHD to the various mechanisms for particle acceleration, such

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