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VI. Solar Radiophysics

(R.T. Stewart)

A. INTRODUCTION

The past 3 years since the last solar maximum have witnessed an unprecedented number (>200) of published scientific papers on many aspects of solar radiophysics. These contributions are the result of an intense research effort mounted during the first Solar Maximum Mission of 1980 and continued until the present. Excellent x-ray, EUV, and visible light observations of the disturbed corona and transition region have been obtained from the SMM, Hinotori, P78-1, and ISEE-3 spacecraft. ISEE-3 also has provided very low-frequency radio observations of solar bursts in the interplanetary medium. Ground-based radio support for space experiments has been provided by many observatories throughout the world. In particular, many collaborative studies using x-ray and radio observations of solar flares have been reported. The outstanding radio instrument during this period has been the VLA, operating at 2, 6, and 20 cm with a time resolution of 10 s and both modes of circular polarization. The two-dimensional spatial resolution of the radio images is a few seconds of arc, almost as good as the best resolution obtained so far at any wavelength in the solar spectrum. To complement the rather poor time resolution of the VLA one-dimensional arrays such as the WSRT at 6 cm wavelength and the Nobeyama interferometer at 17 GHz have been used successfully. In addition, a number of very-high-time resolution radiometers have been built at different locations. At meter wavelengths two-dimensional arrays at Clark Lake, Culgoora, and Nancay and a one-dimensional array at Nobeyama have been employed. The little known region of the solar spectrum at decimeter wavelengths is being investigated by the Zürich spectrograph. It is pleasing to see Chinese participation in solar radiophysics.

Looking ahead there remains only one part of the solar spectrum, from 20 to 1 MHz and corresponding to coronal heights from 3 to 30 $R_\odot$, to be explored. This spectral gap hinders the merging of coronal and interplanetary radiophysics. Another obvious need in the future is for a high time and spatial resolution radioheliograph operating at microwave frequencies, i.e., near 17 GHz. Such an instrument combined with high spatial hard x-ray observations could settle some important questions about particle acceleration and propagation in solar flares, because both the radio and x-ray observations would be viewing emission from the same electron population. For a review of current ideas on particle acceleration in solar flares see report no. VIII by E.R. Priest. For a review on spacecraft observations see report no. IV by K. Tanaka. A review on advances in solar radiophysics has been published recently (Kundu 1982), and a new book on meter-wavelength solar radio astronomy is being published soon (McLean & Labrum 1985).

B. SOLAR FLARE EMISSION

1. Pre-Flare Phase

Observations of active regions showing changes in microwave intensity and circular polarization prior to flare activity have been reported previously. VLA observations show changes in the polarization structure of the flare region just prior to the impulsive phase. These changes may be due to emerging magnetic flux and reconnection (Kundu 1983). Hard x-ray spikes have been correlated with decimeter Type III bursts during this phase (Benz et al. 1983) and show evidence for a downwards motion of the acceleration site as proposed earlier to explain the shift in starting frequencies of Type III bursts (Kane & Raoult 1981). The Type III bursts may be generated by secondary acceleration of electrons outside a flaring loop (Sprangle & Vlahos 1983). Millisecond spike bursts at microwaves occur predominantly during the pre-flare phase (Zhao & Jin 1982). The high degree of circular polarization and brightness temperature ($\sim10^{15}$ K) can be explained by masering at the second harmonic of the gyrofrequency (Melrose & Dulk 1982, Sharma et al. 1982) from a loss cone distribution of energetic electrons in a magnetic loop. The conditions for enhanced spike emission require the plasma temperature to be $<10^7$ K, which may explain why this type of emission seems to be confined to the early stages of the flare event (Holman 1983). Significant plasma heating may occur because of the absorption of electron-cyclotron maser emission at the second harmonic level (Melrose & Dulk 1984). Other models, including plasma emission from runaway electrons, have been proposed (Kuijpers et al. 1981). The size of the source region (and burst brightness temperature) has yet to be confirmed. VLBI measure-ments (Tapping et al. 1983) indicate that the radio flare region can be very small.

2. Impulsive Phase

Theoretical models suggest that the main release of flare energy and particle acceleration occurs at the top of a magnetic loop. Microwave spatial observations, particularly with the VLA, have tended to confirm this picture, in that 2- and 6-cm wavelength impulsive sources often appear near the magnetic neutral line between Hα kernels (Lang et al. 1981). Sometimes bipolar sources are observed, suggesting that the emission comes from the sides of the loop rather than from the top (Kundu et al. 1982). The impulsive burst at microwaves is thought to be due to gyrosynchrotron radiation from trapped electrons in a magnetic loop. Mirroring and other collisions will produce a non-thermal distribution and a general hardening of the electron spectrum even if the initial accelerated distribution is thermal (Holman et al. 1982). Hard x-ray bursts will also be produced by collisions of high-energy electrons in dense regions of the loop. Some evidence from joint hard x-ray and microwave spatial observations exists for streaming of electrons in a loop (Hoyng et al. 1981). Correlation studies between microwave and hard x-ray bursts have been reported by many authors. Some studies (Kane et al. 1983, Kai et al. 1984) argue for a common population of electrons producing the x-ray and microwave bursts at slightly different times because of propagation effects. However, the radio emissivity is critically dependent on the magnetic field strength and spectral index, which makes the close correlation found between hard x-ray and microwave fluxes seen even more remarkable (Kai et al. 1984). Short time delays of ≤0.5 s between hard x-ray peaks and decimeter Type III bursts have also been reported (Kane et al. 1982, Dennis et al. 1984). Such short delays argue for an acceleration region at a considerable height, ~3 x 10^9 cm, above the chromosphere (Dennis et al. 1984). A strong case of weak turbulence effects in the generation of Type III bursts has been determined (Grognard 1982), based on ISEE-3 measurements of the electron distribution function for the electron streat at 1 AU (Lin et al. 1981). A detailed review of Type III burst theory and observations has also been published (Goldman 1983). The controversy between fundamental and second harmonic plasma frequency emission at low frequencies continues.

3. Main Flare Phase

With the large coverage of coronal mass outflows by white-light coronagraphs aboard SMM and P78 it has been possible to study the relationship between the Type II burst shock wave and the leading edge of the coronal transient. In several events there is evidence that the Type II radio emission occurs behind the transient leading edge rather than in front of it, where a piston-driven shock might be expected to form. This result has been interpreted as evidence that the Type II disturbance is a blast wave ejected from the flare, independent of the coronal transient, but producing radio emission upon its intersection with the outflowing material (Wagner & MacQueen 1983, Gary et al. 1984). Statistical studies have shown that 60-70% of Type II bursts are accompanied by coronal transients (Sheeley et al. 1984, Kahler et al. 1984) so that at least 30-40% may be blast waves. Type II bursts appear to be more closely associated with filament channels than with flare regions (Stewart 1984a), suggesting that coronal streamers may be the origin of fast mass transients and Type II bursts. At frequencies below 1 MHz very few Type II bursts have been detected, and these usually have low starting frequencies (Robinson et al. 1984) and are accompanied by interplanetary distrubances such as the magnetic clouds (McKenna-Lawlor & Richter 1983) associated with the homologous Type II bursts of June 27-29, 1980 (Stewart 1984), or with interplanetary mass outflows detected by radio scintillation effects (Watanabe & Kahinuma 1984). The coronal source region of the moving Type IV radio bursts has been observed (Stewart et al. 1982, Gergely et al. 1984) and the density enhancement estimated from white-light measurements to be 30 to 60 times greater than the quiet corona. Such large source densities are consistent with the radio emission arising from Langmuir wave conversion at the second harmonic plasma frequency, although gyrosynchrotron emission cannot be ruled out as an alternative mechanism (Stewart et al. 1982). Other arguments for plasma emission have been advanced (Duncan 1981). A model for electron acceleration in a coronal loop transient suggests that lower hybrid waves are excited at the shock front which then accelerates the tail of the electron distribution within the loop. The resulting plasma emission may be sufficient to explain moving and stationary Type IV bursts (Vlahos et al. 1982). Other evidence for shock acceleration of particles in the corona are the low-frequency SA events observed by ISEE-3 (Cane et al. 1981) at the time of Type II bursts and an electron event associated with the behind-the-limb flare which produces a Type II burst and a meter-wavelength flare continuum (Hudson et al. 1982). Shock-drift acceleration of particles has been suggested as a possible mechanism to explain the herringbone and split-band fine structure in Type II bursts (Holman & Pesses 1983). The close temporal association between gradual hard x-ray and meter continuum bursts during large flares has been advanced as evidence that the x-ray and radio sources are linked by a large magnetic arch and that a continuous common acceleration process takes place. The details of this process are not specified (Klein et al. 1983).

4. Post-Flare Phase

During the decay phase of the solar flare, expanding magnetic loop systems have been observed in Hα, soft x-rays and more recently in microwaves (Velusamy &

Kundu 1981, Nakjima 1982). The radio source region is hotter than the Hα loops and possibly comparable in temperature with the x-ray source, where $T \approx 10^6$ K. The degree of circular polarization is small (Nakajima 1982), indicating thermal emission. For 20-cm wavelength emission the magentic induction is estimated to be B 100 G (Velusamy & Kundu 1981). The radio source initially moves outwards with a speed of ~10 km s^{-1}, comparable with the underlying colder ($T \approx 10^4$ K) Hα loop systems. The post-burst increase may last ~4 h at 17 GHz, thus requiring a continuous heat input to the source region. An exciting discovery by SMM was the gigantic soft x-ray loop systems of arches extending out to heights ~1.5 x 10^5 km above the flare site and visible 6-30 h after a major flare (Švestka et al. 1982a,b). The arch system was stable and associated with an overlying stationary noise storm source region extending out to at least 1.5 x 10^6 km (~2 $R_\odot$). The casue of the noise storm electron acceleration is not certain but it may be due to the emergence of magnetic flux into the corona from the photosphere or due to slow magnetic reconnection following a coronal transient (McLean 1981). Several theories for noise storms have been proposed recently which involve the generation of microturbulence by emerging magnetic flux. The Type I bursts are thought to arise either from the coalescence of ion-acoustic waves and plasma waves (Benz & Wentzel 1981) or from the mode coupling between lower and upper hybrid waves (Spicer et al. 1981). Evidence for a connection between noise storms and emerging flux is the close association beetween noise storms and coronal transients (Lantos et al. 1981, Kerdraon et al. 1983, Duncan 1983), Hα surges (Garczynska et al. 1982), and rapidly growing EUV loop systems (Brueckner 1983). Electron acceleration during the late phase of the flare might occur as a result of magnetic reconnection above post-flare loops. This could explain the apparent temporal association between secondary peaks in microwave outbursts and decameter continuum events (Cliver 1983).

5. Active Regions

The radio emission from active regions, commonly referred to as the slowly varying component, has been studied in considerable detail at microwaves (Alissandrakis & Kundu 1982, Lang & Willson 1982, Dulk & Gary 1983, McConnell & Kundu 1983, Felli et al. 1981, Shibashi et al. 1983, Urpo et al. 1982). The emission seems to be a mixture of bremsstrahlung and gyrosynchrotron emission from thermal distributions of electrons (Seehafer et al. 1983, Pallavicini et al. 1981), with the strongest emission occurring as a broken ring around the sunspot penumbra (Alissandrakis & Kundu 1982, Lang & Willson 1982). Thermal cyclotron lines may also be emitted (Willson 1983). The decrease in microwave emission above the center of the sunspot appears to be due to the presence of a cooler region (Strong et al. 1984). Bright radio sources with brightness temperatures ~3 x 10^6 K appear to be associated with arcades of corodnal loops above magnetic neutral lines (Schmahl et al. 1982). However, some of these bright microwave sources overlie regions of weak magnetic field, which is difficult to explain by gyrosynchrotron emission from thermal electrons unless the loops carry current or unless there is a quasi-continuous low level of particle acceleration from active regions (Webb et al. 1983). It has been suggested that non-thermal electrons might be accelerated in bursts and trapped in magnetic fields of ~100 G for ~1 h to produce the bright microwave sources by gyrosynchrotron emission (Chiuderi & Melozzi 1984). The extension of active region structures outwards into the interplanetary medium has been studied using very low-frequency observations of Type III storms (Bougeret et al. 1984). These storms are closely associated with long-lived Type I noise storms at meter wavelengths and with the slowly varying component at microwaves (Bougeret et al. 1984, Bratova et al. 1983). At meter and decameter wavelengths the Type III storm bursts are polarized in the same sense as the Type I noise storms, but the degree of circular polarization varies considerably, suggesting that the emission may sometimes occur at the fundamental and sometimes at the second harmonic of the plasma frequency (Dulk et al. 1984). Noise storms at metre wavelengths appear to form magnetic sector structures similar to those in interplanetary space (Stewart 1984).

6. Quiet Sun

There has been little work published on this subject over the past 3 years (Kundu et al. 1983, Sastry et al. 1983). Microwave observations of the supergranulation network have been reported (Gelfreikh 1982); the radio brightness temperature is ~10^4 K and the number of sources an order of magnitude less than the number of x-ray bright points.

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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