RADIO OBSERVATIONS OF SOLAR AND STELLAR CORONAE

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ABSTRACT Recent progress in the study of both the solar corona and the coronae of other stars through radio observations is reviewed. We concentrate on selected recent work in solar radio physics, including quiet-Sun fine structure, active region research and flares.

1. INTRODUCTION

In this review we will discuss work using radio observations to study the solar corona, and also the rapidly developing work on radio observations of stellar coronae. Because of space limitations and the availability of earlier excellent reviews of solar radio observations (Kundu 1965; Kundu 1982; Dulk 1985; McLean and Labrum 1985) we choose to emphasize a small number of recent studies from solar radio physics.

2. QUIET-SUN FINE STRUCTURE

The first two-dimensional synthesized radio map of a quiet Sun region was produced by Kundu et al. (1979) at 6 cm with 6 arc sec resolution, using the Westerbork Synthesis Radio Telescope (WSRT). By numerical cross-correlation analysis they demonstrated that the supergranulation network was observable at the level of 6 cm wavelength emission. Autocorrelation analysis showed that the scale of the 6 cm and Ca K network was similar, ~44". Kundu et al. (1979) also showed that many features seen in the 6 cm quiet Sun emission were co-spatial with the chromospheric supergranulation network elements observed in the Ca K spectroheliogram and that the width of the network was similar in radio and Ca K (~15""). From one-dimensional synthesis observations during a partial solar eclipse of a quiet Sun region at 6 cm with an effective resolution of 2.5"x12.7", Marsh et al. (1980) showed that there was no clear correlation of the 6 cm small scale structure with the chromospheric network; they found that at least 3 to 6 radio source positions were consistent with the locations of small bipolar regions, and they suggested that the radio sources might be related to X-ray bright points (BP). Boccia and Poumeyrol (1977) made the speculative suggestion that there could be radio counterparts of X-ray bright points, based upon two-element interferometer observations at 8.6 mm, which did not provide any positional information. Erskine and Kundu (1982) carried out further analysis of the WSRT quiet Sun observations and showed that bright and dark features on the 6 cm quiet Sun synthesized map corresponded to the chromospheric network elements and cells observed in Ca K. Gary, Zirin and Wang (1990) have obtained very high sensitivity VLA observations...
at 8.3 GHz which clearly demonstrate a close association between radio features and optical fine-structure in the quiet Sun.

Two areas in which recent studies of the quiet-Sun have focussed are coronal bright points and macroscopicules.

a. Coronal Bright Points

Solar coronal bright points were first identified in X-rays (Golub et al. 1974); they appear to be assemblages of miniature loops or arches, typically 10-20″ in size. Since the early observations, a great deal of effort has been made to map and study coronal bright points in microwaves, using the VLA. Habbal et al. (1986) were the first to map coronal bright points at 20 cm wavelength and showed that they were similar in behavior to those seen at soft X-ray and EUV wavelengths (Sheeley and Golub 1979, Habbal and Withbroe 1981). Fu et al. (1987) studied bright points at 6 cm, also using the VLA, and demonstrated a similar temporal behavior in many sources.

More recently, Kundu et al. (1987) were able to produce excellent maps of coronal bright points at both 6 and 20 cm wavelengths. They showed that the coronal BP’s had finer structures at 6 cm than at 20 cm, and they were correlated with magnetic bipoles and with dark features in HeI 10830Å spectroheliograms. From the analysis of coronal bright points at 6 cm and 20 cm Kundu et al. came to the following conclusions: 1) Most BP’s are associated with magnetic features. Those which are associated with unipolar magnetic features (10-30% of the total) are possibly manifestations of clumps in the chromospheric network extended to coronal levels. The plage-associated features tend to overlie unipolar magnetic fields. 2) The 20 cm bright points are invariably associated with HeI dark points. Note that the reverse is not true. Presumably, only a few of the coronal mini-loops overlying dark chromospheric HeI features are sufficiently hot and dense to appear bright in microwaves. 3) The brightness temperatures of the bright point sources range from 0.5 - 3 ×10⁵ K at 20 cm and 0.5 - 4 ×10⁴ K at 6 cm. The plage sources have brightness temperatures within the same ranges. These are likely to be the same as the chromospheric supergranulation sources mapped by Kundu et al. (1979). Magnetic elements of the chromospheric network have been shown to produce UV “microflares” (Porter et al. 1987) which resemble the microwave bright points in size (3″×3″), lifetime (20-30 s) and location (over bipoles). The UV events are sufficiently similar to those seen in microwaves that the phenomena may have a common interpretation. The emission mechanism for coronal BP’s in microwaves is thermal bremsstrahlung. 4) The bright points at 20 cm show substructure at 6 cm in all of the strong sources. For the plage-associated sources, the 20 cm sizes are larger than the 20 cm beam, and so the result is not entirely due to better spatial resolution at 6 cm, but may be due to the array’s better sensitivity to large scale structure at 20 cm. However, the bright point sources are more compact and look like the 6 cm sources convolved with the 20 cm beam. Thus the 6 cm maps may show substructures lower in the cluster of loops which form the bright point, while the 20 cm maps show the unresolved, overall structure.

Habbal and Harvey (1987) carried out simultaneous observations of 20 cm bright points and HeI 10830Å dark points, which are believed to be proxies of
X-ray bright points (Harvey et al. 1975; Harvey 1985), and found an overall, but not exact, correlation between the intensities at each wavelength. Comparison of radio maps with magnetograms led them to conclude that bright points occur more often in magnetic cancelling regions than in emerging regions.

Further studies of variability of microwave BP’s were made by Nitta and Kundu (1988). They found that rapid changes in the bright point images were uncorrelated with their intensity, and thereby concluded that temporal variation arose from aggregations of separate miniflares. However, the fact that the change in BP size is uncorrelated with intensity change argues for the time variation being primarily due to short-time variations. This is consistent with the view that a bright point is composed of many small loops, as inferred from soft X-ray and EUV observations (Sheeley and Golub 1979, Habbal and Withbroe 1981) and that the changes in its brightness are due to the brightening of one or more of the mini loops. Sometimes peaks in BP intensity occur in a compact source. It is possible that in such cases we are dealing with brightenings of an elementary loop.

b. Macropicules

The first radio observations of macropicules in solar coronal holes have been carried out by Habbal et al. (1991) with the Very Large Array (VLA) at 4.8, 8.5, and 15 GHz. The macropicules appeared most prominently at 4.8 GHz. Although much less prominent, they appear to be present at higher frequencies also. The brightness temperatures measured in the macropicules at these different wavelengths yield an empirical model consisting of a cool $8 \times 10^5$ K core surrounded by a thin hotter sheath at $1-2 \times 10^5$ K, with the density varying from $10^{10}$ cm$^{-3}$ at the core to $2 \times 10^9$ cm$^{-3}$ at the outer edge. These characteristics are almost identical to those derived from EUV observations more than a decade ago by Withbroe et al. (1976). An important characteristic of macropicules revealed by the 4.8 GHz emission is the pinching off and ballooning at the top of the magnetic structure of the macropicules. There is also evidence in these radio observations that this pinching off leads to the escape of some plasma from the location of the macropicules. These observations point to the importance of monitoring the effect, if any, of macropicules on the solar wind flow.

3. ACTIVE REGION OBSERVATIONS

a. The CoMStOC Campaign: Soft X-ray and Radio Comparisons

The solar corona is known to be dominated by magnetic loops filled with hot plasma. The dynamics and structure of these loops, and the magnetic field and energy density within them, are of great interest in studies of solar activity and flares. In the past, these loops have been delineated and studied, primarily using soft X-ray data from the Skylab and SMM missions. Microwave studies of these loops have been possible using large sidereal arrays such as the WSRT and the VLA.

Soft X-ray emission from closed loops of hot plasma above quiescent active regions is due to thermal bremsstrahlung (free-free) and atomic line
radiation. Microwave emission can result from thermal bremsstrahlung as well as gyroresonance (cyclotron) radiation. Sunspot-associated microwave emission, particularly at 6 cm, is often dominated by gyroemission at low harmonics of the gyrofrequency (Kundu, Schmahl and Gerassimenko 1980). If the temperature and emission measure of the plasma can be determined from the soft X-ray observations, the dominant microwave emission mechanism could be determined at any wavelength. In active regions where gyroemission dominates, the coronal magnetic field strength can be determined.

The Coronal Magnetic Structures Observing Campaign (CoMStOC) was designed to explore these properties of the solar corona and measure its magnetic field. Ideally, simultaneous soft X-ray and microwave observations of quiescent active regions taken by the Solar Maximum Mission’s (SMM) X-Ray Polychromator (XRP) and the VLA can separate the contributions from the two dominant microwave emission mechanisms - thermal bremsstrahlung and gyroresonance - and determine the magnetic field strength and structure in the solar corona. The temperature and emission measure determined from the XRP observations reveal the importance of thermal bremsstrahlung radiation at a given microwave frequency. Where gyroemission dominates, the local magnetic field strength is simply \( B_{\text{ gauss}} = 357 \nu_{\text{GHe}} / n \), where \( \nu \) is the microwave frequency and \( n \) is the harmonic (determined by comparing the radio observations with theoretical models).

The first CoMStOC study was made by Nitta et al. (1991) using a coordinated set of observations obtained on 1987 November 28, using simultaneous microwave and soft X-ray measurements with the Very Large Array (VLA) at 6 and 20 cm and the X-Ray Polychromator (XRP) aboard the Solar Maximum Mission (SMM). Nitta et al. studied two active regions near the solar limb. The images in soft X-rays and at 20-cm wavelength are similar: both show peaks above the active regions and an extended bridge of emission 200,000 km long connecting the two regions. The brightness temperature of the 20-cm emission is lower than that predicted from the X-ray emitting material, however; it is attributed to free-free emission in cooler (\( \leq 10^6 \) K) plasma not visible to XRP, with an optical depth \( \sim 1 \). The 6-cm emission is concentrated at lower altitudes and in a 160,000 km long bundle of loops in the northern active region. Comparison of the 6-cm map with the potential magnetic field lines computed from photospheric magnetic fields (measured two days earlier) indicates that the 6-cm emission is associated with fields of less than 200 G. Such fields would be too weak to attribute the observed 6-cm emission to gyroresonance radiation. Analysis of the 6-cm loop bundle indicates that it is strongly asymmetric, with the magnetic field in the northern leg \( \sim 2 \) times stronger than in the southern leg; the 6-cm emission most likely arises from a combination of hot (\( \geq 2 \times 10^6 \) K) and cool plasmas, while the 20-cm emission becomes optically thick in the cooler (\( 9 \times 10^3 \) K) plasma.

The strongest constraints on the coronal plasma and magnetic field are provided by the 6-cm loop in one of the active regions. To satisfy all the observational constraints, the loop must consist of both hot (\( \sim 2.5 \times 10^6 \) K) and cool (\( \sim 9 \times 10^5 \) K) plasma. Nitta et al.'s use of a two-temperature model is oversimplified in that there is undoubtedly a continuum of temperatures in the loop, but these two temperatures are characteristic of the plasma that is
dominating the emission at X-ray energies and at 20 cm, respectively. The cool plasma must be optically thick at 20 cm (5 - 10) and marginally thin at 6 cm (0.5 - 1) in the brightest region of the 6-cm loop. This model consists of a layer of cool plasma in front of the hot plasma, but it does not rule out a more complex mixture of the hot and cool plasmas as long as the cool plasma becomes optically thick along the line of sight at 20 cm before a significant contribution can result from the hot plasma. The emission measure of the cool plasma is found to be $6 \times 10^{28}$ cm$^{-5}$, as compared to an emission measure $1 \times 10^{29}$ cm$^{-5}$ for the hot plasma. Hence, a "filling factor" 0.4 - 0.6 is obtained for the hot plasma in the loop. In a previous observation requiring cool material, Webb et al. (1987) deduced a $10^{27}$ cm$^{-5}$ emission measure of $10^5$ K material.

The polarization of the 6-cm loop can result from free-free emission in a magnetic field of 175 G if the polarization originates from the hot and cool plasmas together. This is consistent with the magnetic field strength of 190 G at a (rather low) height of 5,000 km extrapolated from the photospheric magnetogram. For the estimated viewing angle of 45 degrees, however, 250 G is required. Hence the required magnetic field strength is somewhat higher than that given by the potential field extrapolation from the Kitt Peak magnetogram. Significantly higher field strengths are required if the polarization originates from either the hot or the cool plasmas alone.

There are several possibilities for reconciling the magnetic field strengths deduced from the photospheric and the coronal data. One is that the magnetic field in the region increased over the two days between the observation used for calculation of the limb fields and the X-ray and radio observations. This cannot be ruled out, although the evidence (based on the magnetogram of the following day) suggests rather that the region was decaying. Another is that the potential field extrapolation is valid, but the magnetogram data were inadequate. Nominally, the spatial resolution of the magnetic observations is 1-2, so regions containing more intense fields would have to be smaller than 1600 km. Alternatively, the magnetogram observations may be adequate, but the extrapolation not justified. The assumption of a potential expansion of the photospheric fields into the corona is only valid if no currents flow. Previous authors (e.g., Alissandrakis, Kundu and Lantos 1980; Schmahl et al. 1982) have also concluded that potential field extrapolations do not provide strong enough fields to match their data and argue that, by relaxing the potential assumption, one can easily obtain stronger fields in the low corona. Schmahl et al. (1982) directly compare the potential solution with a constant-force-free solution which gives stronger coronal fields.

The CoMSiOC study showed that the radio fluxes predicted on the basis of the X-ray data were somewhat in excess of the observed radio fluxes, although the estimated errors in the predicted fluxes are large and formally the observed fluxes lie within the error bars of the predictions. Results from XRP data now appear to be internally consistent. The main difficulty with VLA observations continues to be the problem of missing flux in the longer configurations. It is also possible that the over abundance of ions in the observed regions lead to excessively high values of hydrogen emission measure, which might be responsible for high radio flux prediction.
b. The Strength of Magnetic Fields in the Corona

Based on observations of gyroresonance emission at 15 GHz at coronal temperatures \(7 \times 10^5\) K, White et al. (1991) showed that magnetic fields of at least 1800 gauss can exist in the solar corona. This is the highest reported measurement of a magnetic field in the corona. The strong fields occur in a small source radiating in the extraordinary (e) mode over the penumbra of a large symmetric sunspot. In fact, since the flux from the gyroresonance source is still a significant fraction of the total flux from the active region at 15 GHz, the maximum value of the field in the corona is probably higher than 1800 gauss (the gyroresonant contribution should go to zero at the maximum field). This detection of the presence of high magnetic field strengths in the corona confirms that high energy densities can be stored there which can be released in solar flares.

The optically-thin ordinary (o) mode emission from the region shows a peak at only 36000 K which may be due to a sunspot plume, and a hole over the umbra consistent with the expected low-density material there. Thus there must be a severe inhomogeneity in the corona above the sunspot, and the usual azimuthally-symmetric sunspot models are inappropriate. The picture which is suggested for the relationship between the e peak and the o peak is that both are from a loop originating in the spot and curving up and over towards the trailing part of the active region where the longitudinal magnetic field polarity is reversed. The o source arises in low, cool dense material at the base of the tube, and in projection is therefore offset towards the umbra from the e source which lies at the less-dense coronal heights. The authors speculate that the loop might be identified as a sunspot plume in UV observations. They also argue that the density depression over the umbra may play a much greater role in the observations of ring structure attributed to gyroresonance opacity than has previously been recognized.

4. RADIO OBSERVATIONS OF SOLAR FLARES

a. The Magnetic Topology of the Flaring Region

It is generally believed that solar flares involve the transformation of stored magnetic free energy into plasma energy. One of the aims of imaging studies of solar flares is to identify the magnetic topology of the region in which energy release occurs. This identification can be used to test various flare models, which have different signatures: thus, release of magnetic torsion in a twisted magnetic loop requires only one loop to be present in the flare site, whereas driven reconnection of two adjacent loops or of emerging and pre-existing flux requires two loops.

However, existing images of flares in hard X-rays and microwaves (presently the two diagnostics best suited for observing high-temperature coronal material) are often ambiguous. Both suffer from a restriction common to all types of observation: limited dynamic range. Since the relevant emission mechanisms are not uniform throughout the burst source, this has the result that spatial studies tend to be dominated by the brightest part of a flare, rather than showing the whole structure in which a flare takes place. In the case of hard X-ray images, emission is by bremsstrahlung which favors high densities and hence thick-target...
emission at the feet of flux tubes: thus they usually provide only a cross-section of the coronal morphology. In addition, most hard-X-ray imaging studies refer to low-energy X-rays ($\leq 20$ keV), rather than the higher energy range thought to be more closely associated with the primary energy release in flares (20 to 200 keV).

The gyrosynchrotron process responsible for most flash–phase flare radio emission depends strongly on the strength of the magnetic field and its orientation to the line of sight, which also produces a highly localized peak rather than uniform brightness in the source. The two large synthesis imaging instruments – the WSRT and the VLA – have proven to be the most useful instruments for determining the magnetic topology in solar flares, because they allow high spatial resolution, are generally not dominated by footpoint emission, and by the magnetic nature of the emission process they refer directly to the magnetic fields.

These radio studies have revealed a number of different scenarios for the magnetic topology. The most common seems to be the detection of a compact source over a magnetic neutral line, suggesting a single flaring loop (Alissandrakis and Kundu 1978; Marsh and Hurford 1980; Kundu, Šmahl and Velusamy 1982). Single loops are also suggested by those observations in which two footpoints are apparently observed, or where multifrequency observations suggest high-frequency emission from low in a loop and low-frequency emission from higher in the same loop. Observations interpreted as arcades of loops straddling a neutral line suggest a related picture. On the other hand, Kundu et al. (1982) found evidence for a quadrupole structure, and interpreted their observation as the result of a newly-emerged loop interacting with a pre-existing loop to produce a current sheet and eventually a flare. Kundu et al. (1984) also reported the presence of interactions between multiple structures in a series of flares, while Velusamy et al. (1987) observed complex structure in flaring loops.

The apparent dominance of single-loop structures in flare observations may seem to favor single-loop models for energy release (e.g. Alfvén and Carlqvist 1967; Spicer 1977). However, the limited dynamic range of the observations allows the interpretation that in some cases the observed compact sources may simply be the brightest parts of more complicated interacting structures. Kundu, White and McConnell (1991) presented high-spatial-resolution observations of a small radio burst at 4.9 GHz which appears to show two clear loop structures in the rise phase. This observation favors models in which interaction between structures is involved in the energy release. The brightest location at the peak of the flare lies exactly midway between the two loops, and at this stage the loop structures are not readily apparent. The peak lies away from the H$\alpha$ flare kernels, which however are coincident with probable post-flare loops seen in the radio images. The interesting aspect of this flare is its morphology. The appearance of two elongated structures resembling loops in the rise phase, with a subsequent peak lying exactly between the two loops, is highly suggestive of flare models which invoke interacting loops.

The two loops actually lie on opposite sides of the active region emission, which takes the form of a long ridge. When the flare images are compared with the magnetogram, it is found that indeed these two loops could both join regions of opposite polarity. However, the main burst is apparently not coincident with the H$\alpha$ emission from this flare. The emission from the location of the microwave peak decays rapidly, however, leaving sources coincident with the
Hα kernels at temperatures characteristic of post-flare soft-X-ray loops. These sources subsequently undergo some brightening, and it is simplest to interpret them as indicating dense evaporated and heated chromospheric material, while the emission peak consisted of less-dense but hotter plasma emitting by the gyrosoychrotron process. The lower density of the hotter plasma means that its microwave contribution will diminish rapidly as it cools. The microwave spectrum could be consistent with thermal or non-thermal gyrosoychrotron emission.

As we discussed earlier, the current picture of the morphology of energy release in flares seems to favor both single-loop structures, as well as interacting loops. Further, many observations have been carried out in the VLA's widest configurations, which means that the observations fail to detect much of the total flux from the flare. Nonetheless, there are a number of observations in which these problems do not arise, and which show simple sources overlying neutral lines. This event is another case where observational problems appear to be minimal and a clear picture can be given. In this case interacting loops are implied.

b. Reconciliation of Microwave and Hard X-ray Burst Spectra

Since the early recognition of the similarity of the hard X-ray and microwave time profiles of solar flares, much effort has gone into combining information from the two domains to derive the physical parameters of the source. However, it has been found that the sources of hard and soft X-rays tend to be different, as are the sources of optically-thick and optically-thin radio emission. Multi-wavelength observations in each domain are then required to be confident of the interpretation of an event.

A related difficulty has been the reconciliation of the numbers of energetic electrons needed to explain the hard X-ray and radio observations respectively. It was long held that the number of X-ray emitting electrons was several orders of magnitude larger than the number of radio-emitting electrons, but recently this problem has been ameliorated by the use of a more appropriate model for the X-ray source (thick target rather than thin target; e.g., see Gary 1985; Kai 1986; Nitta and Kosugi 1986; Lu and Petrosian 1988).

Nitta et al. (1991) addressed the relationship between the X-ray and optically-thin radio spectral indices. Non-imaging studies have shown that the radio spectral indices imply flatter electron energy spectra than are deduced from the corresponding X-ray observations with the thick-target model. However, there have generally been ways to avoid this conflict, largely because of insufficient data. Nitta et al. considered a simple impulsive flare (October 1, 1980) which was observed by the VLA at 5 and 15 GHz and by the SMM-HXRB spectrometer in hard X-rays. The radio observations consist of simultaneous imaging data at the two frequencies which show a co-spatial, highly-polarized source. The microwave spectrum was very flat, implying a spectral index of $-1.5$ for the source electron energy spectrum, while the hard X-rays were relatively soft, implying a steeper electron spectrum with an index of 5. They concluded that the overall electron spectrum was steep at lower energies (where hard X-rays were produced) and flat at higher energies (where microwaves were produced). This conclusion has been reached previously, by both radio and X-ray observers, but has not received much
attention; they suggest that such flattening may be common in flares, and that an explanation is required. Such spectra seem to imply that the energization mechanism at energies above the break differs from that at lower energies, and suggests that two mechanisms of acceleration may exist in flares. This will have to be addressed by flare theories.

5. RADIO OBSERVATIONS OF STELLAR CORONAE

If we put the Sun at the distance of the nearest star (Prox Cen), we would not presently be able to detect it with a radio telescope at any frequency. Thus the prospects for stellar radio astronomy amongst main-sequence stars would seem to be bleak. However, one of the remarkable discoveries of the last decade is the fact that a wide range of stellar types are detectable as radio sources. These stars must be intrinsically much brighter than the Sun; it is equally remarkable that they achieve this by having nonthermal coronae apparently quite unlike the Sun’s normal thermal corona, being instead more akin to the flaring solar corona. This result is well correlated with other indicators of solar-like activity, such as strong (thermal) X-ray emission. However, even stellar types (such as magnetic B stars) which should not have solar-like activity, since they lack a convection zone, also show these nonthermal coronae.

In this review we do not have enough space to do a thorough survey of all the classes of radio stars; instead, we will briefly discuss the best known classes, and then briefly mention some of the areas of current research. Amongst those classes of stars which show nonthermal emission but which we will not discuss are OB supergiants, rapidly-rotating chromospherically active single G and K giants and subgiants, W UMa and FK Comae stars, Wolf-Rayets, and cataclysmic variables.

a. RS Canum Venaticorum (RS CVn) binaries. This class of stars contains many of the strongest and most reliable radio stars in the sky, and thus has been well studied. The typical member is a pair of late-type active stars in a close binary orbit, the primary is typically a main-sequence or subgiant star of type F or G, and the secondary is usually a cooler, heavier evolved K subgiant. Algol-like binaries, which contain a hot primary such as a B star plus a cool secondary, seem to have essentially the same properties and we will not distinguish them from RS CVns here. Rotational periods are in the range 1 – 100 days. X-ray observations indicate that these systems have a very hot thermal corona, which is well-fit by single-temperature models with temperatures above $5 \times 10^7$ K. About half of all known RS CVns have been detected as radio sources (Morris and Mutel 1988; Drake, Simon and Linsky 1989). Probably most of the strong radio stars in the sky are RS CVn’s.

Their radio emission may be divided into two phases: a quiescent phase characterized by moderate flux densities, moderate circular polarization and a nearly flat flux spectrum; and a flare phase in which emission is unpolarized, at a high level and has a positive spectral index in the microwave range. These flares may last for days. There is no obvious correlation between binary phase and radio properties. The circular polarization of these stars has two interesting properties: the degree of polarization is inversely correlated with intensity, being small at
all frequencies at outburst; and the sense of polarization in the quiescent state reverses between 1.5 and 5 GHz. The sense of helicity observed from any given system is maintained over timescales of years.

VLBI techniques have been particularly fruitful for RS CVns, for two good reasons: they are strong radio sources; and the separation of the two components, which is thought to be the basic scale length in the corona, is resolvable by VLBI baselines. There have been numerous VLBI observations (e.g., Mutel et al. 1985; Mutel et al. 1987; Lestrade et al. 1988), leading to the following conclusions: the quiescent phase of the radio emission is an optically thin, moderately circularly polarized gyrosynchrotron source which is of the diameter of the binary system, like a common corona; and the flare state is a compact unpolarized optically-thick core much smaller than a stellar radius. All the evidence suggests that the radio emission can be associated just with the active star in the system (usually the cooler component), even though at higher frequencies both components can be active. Both components have brightness temperatures which require nonthermal electron distributions.

b. M Dwarf Stars. This class of stars is apparently the first main-sequence class for which radio detection was claimed. They are an obvious target because many of them are known to display optical flares orders of magnitude larger than solar flares (hence the description “flare stars”). Sir Bernard Lovell pointed the large Jodrell Bank telescopes at them for years, and saw a small number of enormous flares at low frequencies (408 MHz and below), which almost nobody else believed were real (Lovell et al. 1963; Slee et al. 1963). Then in 1977 the first detection of an M dwarf by an interferometer was made, and fittingly it was carried out at Jodrell Bank (Davis et al. 1978). In subsequent work about 40% of the known flare stars within 10 pc of the Sun have been detected as radio sources, and because of the activity cycles of these stars it is believed that nearly one tenth are visible as radio sources at some time. Again, radio detection is well correlated with other activity indicators, including youth (White, Jackson and Kundu 1989).

Of the M dwarfs only the subset known as dMe’s (dM stars with Hα in emission) are detected as radio sources; like RS CVn’s they also show two types of emission: quiescent and flaring. The quiescent emission can have a brightness temperature of up to 10^{10} K, but is more typically 10^8 K, and because the physical size of these stars is so small, current detection levels have only allowed the reliable identification of quiescent emission on a small number of stars (White, Kundu and Jackson 1989). This quiescent emission is unpolarized and varies on a long timescale, much like the emission due to active regions on the Sun. The spectrum can be explained by assuming that the emission arises from a number of active regions, each smaller than the stellar disk but radiating at high brightness temperatures (10^9 – 10^{10} K); however, other models are also plausible and the true nature of this emission has not been convincingly established. Note that K dwarfs which are otherwise as active as M dwarfs seem to be less likely to be radio sources; A and F dwarfs have not been detected as radio sources.

The microwave flares on these stars tend to be quite strange: very high degrees of circular polarization are usually observed, and the flares can last for several hours. After the flares were found to be narrowband (Lang and Willson 1986;
White, Kundu and Jackson 1986), several groups were inspired to carry out
dynamic-spectrum observations which were able to demonstrate the presence
of fine structure in the frequency-time domain (Bastian and Bookbinder 1987;
Jackson, Kundu and White 1987). There seems to be little correlation between
radio flares and flares in other wavelength ranges (optical, X-ray). These radio
flares must arise from some coherent emission mechanism, which presently is not
well understood. The flares are known to be much more common near 1.5 GHz
than at 5 GHz and higher frequencies; also, a given star tends to have flares of one
sense of circular polarization only. Again, the observations appear to require the
presence of nonthermal electron populations as a major component of the stellar
corona; these populations must be confined by strong magnetic fields.

4c. Pre–Main–Sequence Stars. Pre–main–sequence (PMS) stars are known to be
the sites of a variety of extraordinary astrophysical processes, including accretion
disks and outflows. The latter have been detected with observations of molecular
lines in cold gas; here we will only refer to continuum observations. The best–
known PMS stars are the classical T Tauri's, identified by strong Hα emission
lines thought to arise in an extended circumstellar envelope which is an indication
of continuing mass accretion. However, so far these stars have only shown
unpolarized radio emission with a rising spectrum apparently consistent with
thermal bremsstrahlung emission from a strong stellar wind (Cohen et al. 1982;
Bieging et al. 1984; Cohen and Bieging 1986). Thus we have not obtained much
information about their coronae from radio observations. The Herbig Ae/Be stars
are higher–mass PMS stars, and these too have shown radio emission, but this is
probably thermal in most cases.

A related class of stars has only been identified recently, largely on the basis of
their strong X-ray fluxes. These are the so-called “weak–lined T Tauri’s” (WTT’s),
which are apparently stars of similar mass and age to the classical T Tauri’s, but
which lack the extended circumstellar envelope which gives rise to strong emission
lines. The evolutionary status of these stars remains unclear; what is clear is that,
in addition to their strong X-ray activity, they also show strong radio emission,
which is highly variable on timescales of hours (Cohen et al. 1982; Feigelson
and Montmerle 1985). The radio emission is similar in some ways to that of RS
CVn’s, except that so far only very small degrees of circular polarization have been
measured (White, Pallavicini and Kundu 1992). These stars are on average much
farther away than either RS CVn’s or M dwarves since the nearest star–forming
regions are at about 150 pc, so it has been difficult so far to identify whether or not
there is a quiescent radio component in addition to the known flare component.
The nearest WTT may be the southern K0 star AB Doradus, and it is now known
to be perhaps the only star on which rotational modulation of the radio emission
has been observed (Lim et al. 1992). Implied brightness temperatures on these
stars are of order $10^8 - 10^{10}$ K (from VLBI measurements; Phillips et al. 1991),
so again a large nonthermal population of electrons is required in a corona bound
by strong magnetic fields.

4. Chemically–Peculiar (Magnetic) B Stars. This is a class of hot stars, called
magnetic A and B stars, which show peculiar chemical abundances and optical
evidence for kilogauss dipolar magnetic fields. 68 of these stars have now been
observed by the VLA, and about 15 B stars detected (Linsky et al. 1992). They
too show evidence for nonthermal emission: the spectra tend to have negative
spectral indices (Drake et al. 1987), characteristic of nonthermal emission, and VLBI measurements have confirmed that brightness temperatures in excess of $10^9$ K are present, with source sizes less than 6 $R_\star$ (Phillips and Lestrade 1988). Circular polarization typically of about 10% has been observed in many sources, and a weak flare has been seen in one case. Radio emission does seem to be found only in the hotter stars of this class (the B stars); this may be a temperature effect, or may be associated with the stronger winds expected on the earlier-type stars (Linsky et al. 1992).

6. CURRENT ISSUES IN STELLAR RADIOPHYSICS

The fundamental issue is clear: why do stars from such a wide range of stellar types, some of them apparently quite similar to the Sun in many ways, show evidence for coronae which are essentially nonthermal, rather than thermal as on the Sun? (Here we refer only to the radio data; it is clear from the X-ray observations that these stars also contain thermal coronal components, which are usually hotter than the Sun’s.) As we noted above, these nonthermal coronae look more like the flaring solar corona than the quiescent corona. In solar flares nonthermal electrons are produced, but they only cover a small fraction of the solar disk and are usually lost from the corona on timescales of minutes or less due to precipitation into the chromosphere. On stars we seem to need nonthermal populations covering most of the stellar disk, and remaining there continuously. Either the nonthermal electrons can be more easily trapped in stellar coronae for long timescales, or else they must be continuously replenished. In the latter case it is simple to show that the energy requirements for maintaining the nonthermal corona can be a significant fraction of the stellar luminosity (e.g., Kundu et al. 1987).

One obvious answer at a simple level is to argue that these stars do have continuous solar-like flaring due to dynamo-induced magnetic activity, which is much more vigorous than on the Sun. This explanation requires a convection zone, and thus cannot be used with magnetic B stars. However, as noted above, in the case of magnetic B stars we can use the stellar wind as a plausible source of free energy for accelerating electrons; this source does not exist for cooler dwarfs. The solar analogy at this level is also not particularly helpful in suggesting what observations are needed to proceed further in understanding stellar activity. It is clear that close contact with research from other wavelength ranges will be an important part of progress in this area.

The knowledge of different classes of stars offers an opportunity to relate their differing radio properties to the different conditions in the coronae. For example, the surface gravity on a late-type M dwarf is much stronger than on a cool subgiant, or on the Sun; the density at the base of the corona on these stars will differ accordingly. Comparisons of how details such as these affect radio properties may prove to be revealing. For example, we have argued that the reason RS CVn’s do not show more coherent radio flares of the type prevalent on M dwarf flare stars is because the coronae are optically thick to radio emission at a height above the layer where such flares are produced (White et al. 1990).
There are many similarities between the active pre-main-sequence low mass stars and the most active class of main sequence dwarves, the M dwarf flare stars. In fact it is well known that the most active flare stars lie above the main sequence on the HR diagram, and thus are still in the last stage of their contraction onto the main sequence. They are therefore young stars, and the obvious question is whether they are truly distinct from the WTT stars. From the radio point of view, the two classes are quite different. The radio emission of M dwarfs is dominated by narrowband highly-polarized coherent flares, whereas the weak-lined T Tauris show more conventional nonthermal incoherent flare emission, with low polarization and relatively long rise and fall times (hours). Also, the WTT's are all further away than most M dwarfs known to be radio sources, so they must on average be more luminous. The WTT's are certainly younger than the known flare stars, so the question arises: as these low mass stars evolve towards the main sequence, how does their radio emission change? Do they go through an intermediate-age period when they cease to be detectable radio sources? This is suggested by the lack of radio detections in the intermediate-age Pleiades (Bastian et al. 1988) and Hyades (White, Jackson and Kundu 1992) clusters. This seems to imply that the activity seen in the WTT phase may not be associated with convection. This type of argument has not received much attention as yet.

The emission mechanism for the coherent flares observed on flare stars and occasionally on RS CVn's is not understood. Considerable effort has been made to interpret it on the basis of our knowledge of similar emission mechanisms on the Sun, but it is sufficiently different (extends to high frequencies, long-lasting) that there is no convincing interpretation as yet. In any case, for stellar physics in general the use of these observations to interpret conditions in the corona will probably be more useful than a detailed understanding of the emission mechanism itself. Since it is narrowband, we know that the radiation must be at a harmonic of either the local plasma frequency or the electron gyrofrequency, the only known relevant characteristic frequencies of the medium. This information together with information derived from studying quiescent emission can be used to investigate coronal conditions.

7. PERSPECTIVES IN SOLAR RADIO PHYSICS

Solar Radio Physics is a mature discipline. In fields such as this, discoveries are centered around developments of powerful new instruments. Over the past decade several radio telescopes have played key roles in discoveries of new phenomena and better understanding of physical processes in the sun's atmosphere involving the quiet sun, active regions and flares. These radio telescopes are the WSRT and the VLA at centimeter-decimeter wavelengths, and the Clark Lake multifrequency radioheliograph and the Nancay radioheliograph at meter-decimeter wavelengths. Independently and along with Skylab, SMM and HINOTORI space mission observations, these instruments have allowed us to discover: (a) new quiet sun fine structure, supergranulation networks, coronal bright points and polar macrospicules in microwaves; (b) microwave emission from active region loops, some of which are also observed in soft X-rays; specifically they have permitted us to confirm the gyroresonance radiation interpretation of the sunspot-associated microwave radiation and thereby allowed the determination of coronal magnetic fields; (c) the magnetic field topology in flare energy release.
sites, in particular they have permitted the determination of the relative positions of microwave burst and hard X-ray burst sources in flaring loops, thereby providing constraints to flare theories; and they have also provided evidence of both single loops as well as interacting multiple loops as sites where flare energy release takes place; (d) radio signatures at meter-decimeter wavelengths of coronal mass ejection events (CME's), especially slow CME's and meter-decimeter wavelength microbursts; they have provided new insights into particle acceleration processes.

The next decade (1990's) will see the growth of radio studies of high energy solar physics, combining millimeter imaging instruments such as BIMA (Berkeley-Illinois-Maryland Millimeter Array) and space missions such as the Gamma Ray Observatory, Yohkoh and the High Energy Solar Physics mission (HESP). We already have results to indicate that millimeter emissions are a powerful diagnostic of the solar flare \( \gamma \)-ray-emitting electrons. Yohkoh has already proven to be extremely powerful by providing tens of thousands of high-quality images which have delineated all kinds of flaring structures, single loops, interacting loops, and as yet undefined complex loop systems. It will be a big challenge for both the VLA and BIMA to single out a few loop systems in coordination with Yohkoh and to do the necessary physics from the point of view of flare theories. The next decade will also see the completion of the Very Long Baseline Array (VLBA), which has the potential of making fundamental contributions to both solar and stellar radio physics through its ability to resolve milliarcsecond (km-sizes on the Sun) structures.

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