GYROSYNCHROTRON EMISSION OF SOLAR FLARES*

(Invited Review)

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Abstract. The current status of our knowledge on the theory of radio emission from mildly relativistic electrons and its application in the interpretation of solar radio bursts are reviewed. The recent high spatial resolution microwave observations have given important information about the geometry of the emitting region and have helped in the computation of better inhomogeneous models that reproduce qualitatively several observational characteristics of the emission. The limitations of the observations and the theory (particularly the effect of mode coupling on the observed polarisation) are pointed out and the potential of the gyrosynchrotron process as a diagnostic of the physical conditions is discussed. This will help us to obtain quantitative information about the changes of the magnetic field and the acceleration of particles in solar flares.

1. Introduction

Sporadic solar radio emission shows an extraordinary variety of structure in frequency, time and space, some of which is beyond or at the limit of our present observing facilities. In spite of this 'zoo' of fine structure there is an important component of the emission which is both broad-band in frequency with no appreciable drift and relatively slowly varying (i.e., with time-scales from about tens of seconds up to more than one hour). This component is generally referred to as continuum and includes the metric and decametric type IV bursts as well as the microwave bursts. Both are important manifestations of the energy released in the course of solar flares and their observational and theoretical study provides information both about the radiation processes involved and the physical conditions in the corona.

The metric type IV emission was first attributed to synchrotron radiation from 3 MeV electrons by Boischot and Denisse (1957), while Takakura (1959) interpreted the microwave bursts in terms of the same physical process from 10 keV to 1 MeV electrons. There are now serious doubts about the origin of type IV bursts, while the observational evidence shows that the electrons responsible for the impulsive phase of microwave bursts are mildly relativistic with energies up to a few hundred keV, so that the synchrotron approximation is not applicable. The computation of this gyro-synchrotron emission is considerably more involved, however important progress has been made since the early days (e.g., Takakura, 1967; Ramaty, 1969).

It is important to note that, together with the free-free process, gyrosynchrotron is the best understood radiation mechanism at radio wavelengths. Consequently it is a very useful tool for the diagnosis of the magnetic field and, together with the hard X-ray

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emission, of the energy distribution of the radiating particles. It is, therefore, not surprising that there has been renewed interest in it, as a result of the recent high resolution observations of microwave bursts. Since there is already a number of books and reviews related to the subject (Kundu, 1965; Takakura, 1967; Zheleznyakov, 1970; Krüger, 1979; Melrose, 1980; Kundu and Vlahos, 1982) the purpose of this review is not to present an exhaustive treatment of gyrosynchrotron emission, but rather to give a comprehensive account of our present knowledge and to convince the reader that detailed modelling is well within our present capabilities. To this end, the importance of recent observational and theoretical work is pointed out and suggestions for future work are made.

2. Radiative Transfer and Emission Mechanisms

The interpretation of the observed properties of the emission in terms of the physical conditions of the radiating plasma requires a thorough treatment of both the emission mechanisms and the radiative transfer. In the past, little attention has been paid to the latter, which is equivalent to assuming a homogeneous source; however, it is now possible to observe the inhomogeneous structure and thus a full treatment of the radiative transfer is necessary.

Details about the subject of this section can be found in several publications, so here I will only give a brief description of the problem and I will point out the more important aspects. In a magnetised plasma the electromagnetic radiation is usually described in terms of the specific intensity, I_j, of the extraordinary ($j = 1$) and ordinary ($j = 2$) modes. Then the transfer equation has the form:

$$\frac{\mathrm{d}}{\mathrm{d}\tau_j}\left(\frac{I_j \cos \Theta_j}{n_j^2}\right) = \frac{\cos \Theta_j}{n_j^2}(I_j - S_j)\,, \tag{1}$$

where n_j is the index of refraction; Θ_j, the angle between the wave vector and the group velocity; S_j, the source function ($S_j = \alpha_j/k_j$, where α_j is the emission and k_j the absorption coefficient); and τ_j, the optical depth ($\mathrm{d}\tau_j = -k_j\,\mathrm{d}s$, s being the length along the direction of propagation measured from the source to the observer). In LTE the source function for each mode is equal to one half of the Plank function ($S_j = kT_e/\lambda^2$). Unlike the optical case, in the radio domain the source function does not depend on the radiation field, thus the emerging specific intensity can be computed from the formal solution of the transfer equation:

$$I_j = \int_0^\infty \frac{\cos \Theta_j S_j}{n_j^2} e^{-\tau_j}\,\mathrm{d}\tau_j\,. \tag{2}$$

Quite often the simplifying assumption $n_j \simeq 1$, $\Theta_j \simeq 0$ is made, which is in general valid for low plasma density and high frequency.

From the observational point of view it is more convenient to describe the radiation in terms of the Stokes parameters. The resulting equations are very complicated (e.g., Krüger, 1979), however, for a homogeneous medium at the limit of large Faraday rotation and no mode coupling fairly simple relations are obtained:

$$I = I_1 + I_2, \qquad Q = I_1(1 - K_1^2)/(1 + K_1^2) + I_2(1 - K_2^2)/(1 + K_2^2),$$
$$U = 0, \qquad V = 2(I_1 K_1/(1 + K_1^2) + I_2 K_2/(1 + K_2^2)). \tag{3}$$

In the above expressions $K_j = -iE_{yj}/E_{xj}$ are the transverse polarisation coefficients (e.g., Zheleznyakov, 1970); E is the amplitude of the electric field of the wave which propagates along the z-axis, while the magnetic field is on the $y - z$ plane.

Under conditions of quasi-longitudinal (QL) propagation, $K_1 \simeq 1$, $K_2 \simeq -1$, and we obtain $Q = U = 0$ and $V = I_1 - I_2$, so that the polarisation is circular and has the sense of the e-mode if $I_1 > I_2$. The other extreme is quasi-transverse propagation (QT) which, under solar conditions occurs when the direction of wave propagation is almost perpendicular to the magnetic field. In this case $K_1 \to 0$, $K_2 \to \infty$, $Q = I_1 - I_2$, U $= V = 0$, so that the polarisation is linear. However, due to the large Faraday rotation in the corona, linear polarisation can only be observed with receivers of much narrower bandwidth than those currently in use.

The computation of the circular polarisation observed on the Earth is further complicated by the effects of mode coupling, which occurs in regions where the dispersion curves of the two modes approach each other, as for example when $\omega_p/\omega \ll 1$, where ω_p is the plasma frequency and ω the frequency of the wave. The coupling is usually described in terms of the coupling parameter, C, (Cohen, 1960; Zheleznyakov and Zlotnik, 1963; Zheleznyakov, 1970; Bandiera, 1982). When $C \ll 1$ (weak coupling) the waves retain their identity as they propagate and the polarisation changes along the path in accordance to the local values of the polarisation coefficients and Equations (3). When $C \gg 1$ (strong coupling) a transformation of waves of one type into the other occurs and the polarisation remains fixed.

Under conditions prevailing in the solar corona the coupling coefficient increases with height and frequency. When the propagation conditions are QL along the entire path, the limiting polarisation is circular with the same sense as in the source, since the region of critical coupling ($C = 1$) is high in the corona where the polarisation coefficients are close to unity. However, when the waves pass through a QT region one of the following will happen: (a) If $C \ll 1$ the sense of circular polarisation is reversed due to the reversal of the magnetic field component along the line-of-sight; (b) if $C \simeq 1$ the polarisation becomes linear; and (c) if $C \gg 1$ the ordinary wave is converted to an extraordinary and vice versa, so that there is no reversal in the sense of circular polarisation. Thus unless the propagation is QL or the coupling strong in QT regions, the observed polarisation will not correspond to the polarity of the magnetic field at the region of formation of the radiation.

Probably the best observed case of polarisation inversion is the one reported by Kundu and Alissandrakis (1984), who followed an active region for 6 days as it crossed the solar disk. In the case of bursts, observations of the reversal of the sense of circular polarisation of the flux as a function of frequency (Kakinuma, 1958) as well as its statistical dependence on heliographic longitude (Krüger, 1976) are most likely due to mode coupling (Cohen, 1961). More recently Alissandrakis and Preka-Papadema (1984) found that coupling effects in a flaring loop can be important even at wavelengths as short as a few cm, unless the magnetic field drops sharply outside the flaring loop.

The integration of the transfer equation requires the knowledge of the radiation processes which specify the absorption and emission coefficients. For the continuum emission of radio bursts two processes should be taken into account: free-free (bremsstrahlung) emission from ambient thermal electrons and gyrosynchrotron emission from electrons gyrating in the magnetic field. Although bremsstrahlung has a negligible effect in the emission, it is important because it increases the optical depth in dense regions such as the chromosphere or the low corona.

Gyrosynchrotron radiation may originate from electrons having either a non-thermal or a thermal distribution; in the latter case they could be ambient thermal electrons or electrons heated as a result of the flare processes. A single electron will radiate at discrete frequencies:

$$\omega = \frac{s\omega_H/\gamma}{1 - n_j\beta \cos\theta \cos\phi}, \tag{4}$$

where s is the harmonic number; ω_H the electron gyrofrequency; β, the velocity of the electron in units of the velocity of light; γ, the Lorentz factor; θ, the angle between the magnetic field and the line-of-sight; and ϕ, the pitch angle of the electron. One can see immediately from Equation (4) that an isotropic distribution of monoenergetic electrons will emit at a harmonic s with a bandwidth of $\Delta\omega/\omega = 2n_j\beta\cos\theta$; further broadening results from the energy spread of the distribution function, so that for mildly relativistic electrons we get a quasi-continuum emission over a large frequency band.

The usual approach for the computation of the emission is that of a single particle radiating in cold plasma (e.g., Liemohn, 1965; Ramaty, 1969; Ko, 1973), while for the thermal case some authors have used the kinetic equation approach (e.g., Gershman, 1960). The resulting expressions for the emission and absorption coefficients for an ensemble of particles involve integration over the distribution function, summation over harmonics, as well as Bessel functions. Simplified expressions have been given by Petrosian (1981) and by Dulk an Marsh (1982); these have a limited range of validity, but they are nevertheless useful in some applications. Since they are valid above the tenth harmonic, if the magnetic field is 500 G they cannot be used at wavelengths larger than 2 cm. At very high harmonics (above the 50th) one can also use the synchrotron approximation, provided that the effects of the high energy cut-off are not important.

The spectrum of the emission and absorption coefficients gives some information about the spectrum of the intensity of the radiation (Takakura, 1967; 1972; Ramaty, 1969; Holt and Ramaty, 1969). Their spectrum shows a maximum at low harmonics of the gyrofrequency. In the synchrotron approximation the slope of the high frequency part of the spectrum is $(\Gamma - 1)/2$, where Γ is the slope of the isotropic power-law distribution of the radiating electrons; in the real case the slope is higher due to the effects of the high energy cut-off in the distribution function. If the particles have an anisotropic pitch angle distribution, the emissivity is suppressed if the direction of observation is not close to the direction of maximum anisotropy. Pitch angle anisotropy can lead to masering action in the ordinary mode by making the absorption coefficient negative.

The low-frequency part of the spectrum is shaped by the effects of the ambient medium and radiative transfer. For large ambient density the index of refraction approaches zero at low frequencies and both the emission and the absorption coefficient are suppressed; this results in the supression of the intensity which is known as the Razin–Tsytovich effect. Moreover, if the optical depth of the radiating particles is greater than unity, as is often the case at low frequencies, then the intensity spectrum falls below the spectrum of the emission coefficient; this is the self-absorption effect, which shifts the maximum of the intensity spectrum to the third or higher harmonics of the gyrofrequency.

The emission coefficient is larger for the *e*-mode than for the *o*-mode, while the inverse is true for the source function. Thus the polarisation of an optically thin region is that of the *e*-mode, while an optically thick region will have *o*-mode polarisation. Since the same region can be optically thin at high frequencies and optically thick at low, this provides an alternative interpretation for the observed change of the sense of circular polarisation with frequency.

When the electron distribution is thermal, simpler expressions are obtained. For coronal temperatures the thermal electrons are non-relativistic, and the first term of the power series expansion of the Bessel functions is sufficient (Zheleznyakov, 1962). In this case the absorption coefficient has a line spectrum (gyroresonance emission), however the spectrum of the intensity is continuum due to the variation of the magnetic field and the temperature with height. Gyroresonance is the dominant process for suspot associated emission at cm wavelengths. It is also important for bursts, since the ambient thermal electrons are optically thick to the extraordinary radiation up to the third or fourth harmonic and to ordinary radiation up to the second or third harmonic, provided that the angle between the magnetic field and the line of sight is not too small.

For larger temperatures, expressions for thermal distributions have been obtained by Drummond and Rosenbluth (1960) in connection with fusion plasmas and by Dulk *et al.* 1979), Petrosian (1981), and Dulk and Marsh (1982), in connection with solar flares. The latter work was prompted by suggestions (Mätzler, 1978; Crannel *et al.*, 1978) that microwave and hard X-ray burst emission may come from hot thermal electrons ($T_e \simeq 10^8$–10^9 K) rather than from a non-thermal distribution.

The above discussion shows that we understand fairly well the various physical aspects of gyrosynchrotron emission. Thus it is important to go back to the observations and exploit the wealth of information provided by them.

3. Observations

As was pointed out in the introduction, gyrosynchrotron radiation has been invoked in the interpretation of impulsive microwave bursts and metric type IV bursts. The former occur at, or very close to the energy release site of solar flares. Our present picture is that part of the energy released goes into particle acceleration and heating (for a recent account see Vlahos *et al.*, 1986); the energic particles radiate as a result of their interaction with the magnetic field. The situation with type IV emission which originates higher up in the corona is more complicated (see reviews by Pick, 1986; Trottet, 1986); the gyrosynchrotron process is still a candidate, at least for part of the emission from moving type IV bursts, however the high brightness temperature ($> 10^9$ K) observed in some of them, the lack of circular polarisation at their beginning as well as the requirement of significant Razin suppression indicate that plasma radiation may provide an alternative interpretation. An equally important question is the confinement of energetic electrons, particularly in the 'isolated source' variety of the emission. As for decimetric bursts, when they are not extensions of microwave or metric bursts they have too narrow a bandwidth to be compatible with gyrosynchrotron emission (Benz and Tarnstrom, 1976). We are thus left with microwave bursts as the best case to apply the gyrosynchrotron process and in this section I will review the relevant observations.

The ideal observation is one with high spatial resolution, adequate time resolution and wide frequency coverage. This is not attainable with present day instruments, so that the observer can have only one of the above at a time. In addition it is important to have observations in other spectral regions, such as optical, *EUV*, soft and hard X-rays. The latter are particularly important since they also originate form high energy electrons, while *EUV* and soft X-rays provide information about the thermal part of the flare; finally Hα and photospheric magnetic field observations are important in deducing the geometry of the flaring region and its association with the active region magnetic structure.

Before the advancement of large aperture synthesis instruments the observations were limited to studies of the flux spectrum with occasional interferometric observations (Kundu, 1965; Castelli and Guidice, 1976; Kundu and Vlahos, 1982). Such observations are still made by the world- wide solar patrol network as well as more involved instruments such as that of Bern Observatory. Although there is considerable variation from one event to another, during the impulsive phase the flux spectra are in general broad band with a maximum around 6 cm; later in the course of the event the spectra flatten and attain thermal characteristics. When the emission extends to metric wavelengths the flux shows a minimum somewhere in the decimetric range; this most probably shows that the microwave and the metric emission originate in two different regions in the corona (Kundu and Vlahos, 1982).

Several attempts have been made to derive estimates of the physical conditions in the source from the flux spectra. Using the arguments presented in the last section, one obtains a magnetic field of a few hundred gauss and a spectral index of 3–5. A lot of the early modelling concerned the apparent discrepancy between the number of energetic electrons deduced from microwave spectra and that deduced from hard X-ray spectra under the assumption of thin-target emission (Holt and Ramaty, 1969; Takakura, 1972). Considering the complicated dependence of both emissions on the physical conditions and the source geometry, this problem cannot be resolved without a proper treatment of these factors in inhomogeneous models.

Early interferometric observations (Kundu, 1959) showed that the size of impulsive sources is of the order of 1′, implying brightness temperatures of 10^7–10^9 K. Using the fan beam Toyokawa interferometer, Tanaka *et al.* (1967) observed a burst where the emission originated in two sources of opposite circular polarisation, while Enome *et al.*, (1969) measured sizes of about 30″.

During the Skylab mission solar observations were undertaken with the NRAO 3 element interferometer at 3.7 and 11 cm with a few arc sec resolution (Hobbs *et al.*, 1973; Kundu *et al.*, 1974; Lang, 1974; Alissandrakis and Kundu, 1975). Although the u-v coverage was insufficient even for 1-dimensional mapping, these observations revealed the presence of structures with spatial scales of a few arc sec and brightness temperatures of 10^7–10^9 K which were not located at the same position as the brightest pre-existing source. During the same period observations were also obtained with the Stanford 5 element interferometer at 2.8 cm (Felli *et al.*, 1975) with a 16″ resolution and showed that the burst emission consisted of several components. Comparison of the radio observations with Skylab soft X-ray images (Kundu *et al.*, 1976; Pallavicini and Vaiana, 1976) showed a good correspondence of position and size.

The modern era of cm observations opened with the use of the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA). These instruments are available for solar observations only for limited periods, therefore observations with lower resolution, dedicated solar instruments such as the Nobeyama interferometer (Nakajima *et al.*, 1984) are important. Using the WSRT, Kundu and Alissandrakis (1975) and Alissandrakis and Kundu (1978) made one-dimensional observations of weak bursts at 6 cm with a resolution as good as 6″. Most of the bursts had a simple structure with sizes of 7–23″, brightness temperatures up to 2×10^7 and were located near neutral lines of the magnetic field.

The use of the VLA made possible the construction of two dimensional maps of burst sources with a spatial resolution as good as a fraction of an arc second and time resolution of 10 s (Marsh and Hurford, 1982; Kundu and Lang, 1985). The most important result is probably the detection of changes in the magnetic field prior, during and after the impulsive phase (Kundu *et al.*, 1982b; Willson and Lang, 1984). However, an equally important aspect is the geometry of the source and of the magnetic field, which can give us a better understanding of the emission and a subsequent interpretation of the observations. Untill now about 50 events have been described in the literature, observed at 2, 6, and 20 cm; all but a few were observed at one wavelength only, so that the information we have about the change of structure with frequency is limited. A much better frequency coverage is provided by the frequency-agile interferometer of the Owens Valley Radio Observatory (Hurford, 1986), without imaging capability but with sensitivity to small sources.

At 6 cm weak bursts often consist of a single source with size of 3–8″ and brightness temperature of 10^7–10^8 K, above a broader background (Kundu *et al.*, 1981). Strong bursts consist of many such sources, rapidly varying in time, with peak brightness temperatures up to 3.5×10^9 K (Kundu *et al.*, 1982a; Velusamy and Kundu, 1982); these compact sources may occupy and area of about 20″ by 40″. Observations at 2 cm have shown sources as small as 2″ (Marsh and Hurford, 1980) while at 20 cm sources larger than 30″ (Willson, 1983, 1984; Willson and Lange, 1984) as well as post flare loops (Velusamy and Kundu, 1981) have been observed. I should note here that a synthesis instrument, as well as an interferometer, is not sensitive to large sources due to the lack of sufficiently short baselines; this sensitivity is reduced at short wavelengths. Moreover, a synthesis instrument detects less flux than a full-disk patrol instrument and this is a clear indication that, in addition to the observed compact sources, there is also a broad, weaker emission (Alissandrakis and Kundu, 1975, 1978).

In general there is good positional correlation of the bulk microwave, Hα and soft X-ray emissions, within the alignment errors of 5–10″. In more detail, more often than not, impulsive burst sources span the neutral line of the magnetic field connecting Hα ribbons of opposite polarity (Figure 1), with the emission maximum located between the ribbons. The extent of microwave sources parallel to the neutral line is usually smaller than that of the Hα ribbons. In some case compact bursts were observed at 1.3 and 2 cm, which were located between the Hα kernels without any connection with them (Marsh and Hurford, 1980; Marsh *et al.*, 1981). On the other hand, Kundu *et al.* (1982a) at 6 cm and Willson (1984) as well as Willson and Lang (1984) at 20 cm observed sources consisting of two components with opposite sense of circular polarisation suggesting emission from the footpoints of flaring loops. Kattenberg and Alaart (1983) using the WSRT at 6 cm observed emission from two sources, correlated in time but with different characteristics, while Alissandrakis and Kundu (1986; see also Vlahos *et al.*, 1986) found that 57% of the 76 bursts observed with the WSRT in 1980 had double or multiple structure; in many cases the two components of a burst were joined by a bridge of low intensity emission. Studies of the relative positions of soft X-ray and microwave sources have shown both coincidences (Hoyng *et al.*, 1983; Kattenberg *et al.*, 1983) as well as displacements of about 20″ (Kundu *et al.*, 1984; Kahler *et al.*, 1984). More recently Alissandrakis *et al.* (1986) found a good correspondence between 6 cm burst emission and soft X-ray loops; compact loops were associated with single sources at 6 cm, while in extended loops the 6 cm emission showed maxima near the footpoints.

Comparisons of circular polarisation (V) maps with photospheric magnetograms often show considerable differences. The 6 cm V maps have a lot more structure than the magnetograms (Kundu *et al.*, 1982a; Velusamy and Kundu, 1982) with dipole or quadrapole structures inferred in regions wherre no such indication is given by the magnetograms. These structures change with time and they have been interpreted in terms of flare-associated changes of the magnetic field in the low corona (Kundu *et al.*, 1982b). When the V pattern is simpler (Marsh *et al.*,, 1981; Kundu *et al.*, 1982a; Hoyng *et al.*, 1983) the sources are often bipolar with the line of zero V passing through the peak of the total intensity source; however, it is often displaced with respect to the

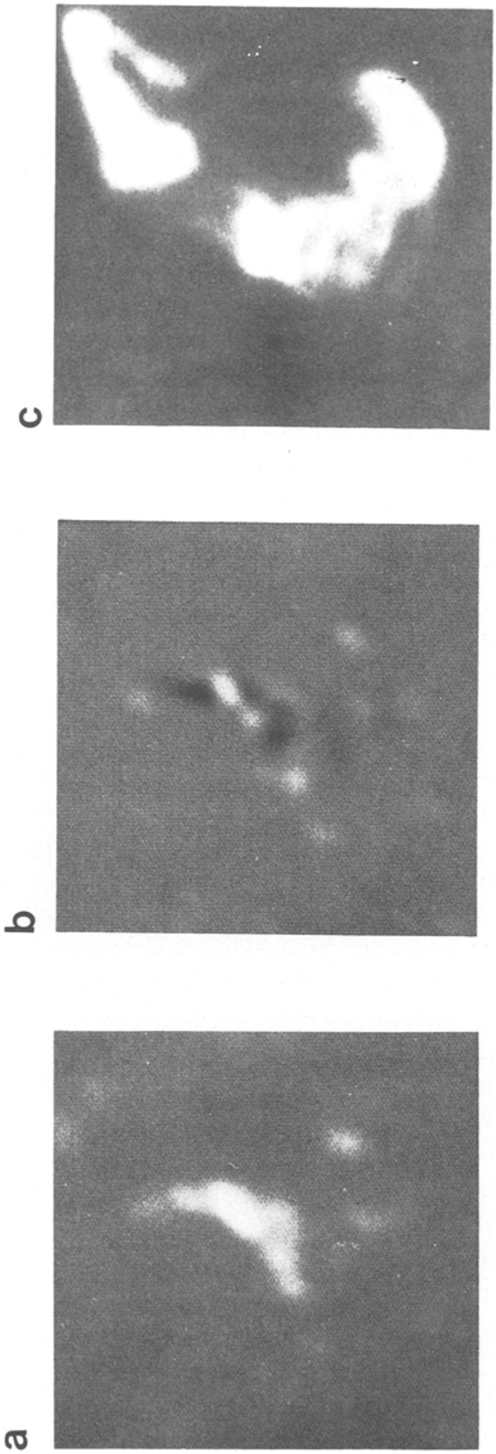

Fig. 1. Maps of total intensity (a) and circular polarisation (b) at the peak of a 6 cm burst; the associated Hα flare is shown in (c). The field of view is 40″ by 48″ and the resolution 3″ by 2″ (from Velusamy and Kundu, 1982).

photosperic neutral line, probably due to a difference in height or due to wave propagation effects. The sense of V is usually that of the extraordinary mode, with one reported case of ordinary mode polarisation (Kundu *et al.*, 1982a). In the bursts studied by Kattenberg and Alaart (1983) the component with fast time variation was unpolarised and the more gradual component was polarised, while in only 10% of the double peaked bursts studied by Alissandrakis and Kundu (1986) the two components were polarised in the opposite sense.

Simultaneous observations at 2 and 6 cm have shown that in some cases the maxima of the emission at the two wavelengths were cospatial (Kundu, 1983; Shevgaonkar and Kundu, 1985), while in others two sources of 2 cm emission were located at the edge of the larger, elogated 6 cm source (Shevgaonkar and Kundu, 1985), suggesting emission from the entire flaring loop at long wavelengths and footpoint emission at short wavelengths. This appears consistent with the results of Dulk *et al.* (1986), although they observed only one compact source at 2 cm at the edge of the 6 cm source; it is possible that due to the asymmetry of the loop the other source was too weak to be observable.

Although every flare has its own peculiarities, it is important to establish a 'working model' on the basis of the observations described above. In the line of our current thinking about solar flares, the high resolution observations are consistent with the geometry of a magnetic loop, either isolated or, more probably, interacting with other loops. Such an 'elementary' burst loop spans the neutral line of the photospheric magnetic field and has its footpoints in Hα ribbons. The loop is filled with thermal plasma at a temperature of about 10^7 K and a density near 10^{10} cm^{-3} which emits soft X-rays and contains energetic electrons which emit in microwaves and hard X-rays. The microwave radiation comes from a large part of the loop while its maximum can occur either near the top or near the feet of the loop; the latter is more likely at short wavelengths. The sense of circular polarisation is sometimes that of the extraordinary mode, with the zero polarisation line passing near the top of the loop; however, this is not always the case and many variants exist. In this model the hard X-rays are produced as a result of thick target emission from electrons precipitating at the footpoints and/or thin target emission from trapped electrons.

The above picture does not describe in a satisfactory way those 2 cm observations which indicate that the emission is confined in a small region above the neutral line. If we exclude observational effects such as the lack of sensitivity to extended sources, this type of emission can arise either in very compact, low lying loops, or at the top of larger loops. In the latter case, either the electrons are somehow confined at the top of the loop, or the physical conditions at the top are much more favourable for gyrosynchrotron emission than at the feet of the loop.

4. Inhomogeneous Models of Burst Emission

The fine structure of microwave bursts shows quite convincingly that it is practically impossible to describe the emission in terms of homogeneous models. This remark applies to the spectral as well as to the spatial characteristics. The first inhomogeneous models (Takakura and Scalise, 1970; Takakura, 1972) were based on the magnetic trap concept proposed by Takakura and Kai (1966) which, although it is now twenty years old, it is very close to our present views. The concept of the flaring loop was unknown at the time and thus it was assumed that the radiation came from a large region between the footpoints; the limits of the emitting region were set, somewhat arbitrarily, by assuming no emission in low field regions. The model was used for the computation of flux spectra and the study of self-absorption and the Razin effect. Using models developed along similar lines, flux spectra were computed by Kovalev and Korolev (1976) and Böhme *et al.* (1977); the latter used a non-thermal core–thermal halo model.

When the first VLA observations appeared there was an interest in models predicting emission from the top of the loop. The emission in the high frequency part of the spectrum increases with the magnetic field and with the angle θ between the field and the line-of-sight. For a loop located near the center of the disk the intensity of the magnetic field is low and θ high near its top, while the inverse is true at the footpoints. Therefore, in order to have emission from the top of an optically thin loop, the magnetic field should decrease slowly from the feet to the top of the loop. This was the conclusion of Petrosian (1982), who used a simplified semi-circular magnetic loop model, simplified expressions for the emission coefficient and computed the total intensity along the loop without solving the transfer equation (optically thin approximation). The difficulty with this model is that a loop with almost uniform magnetic field will not be efficient in trapping the electrons.

More recently, models of the spatial structure of flaring loops were computed by Alissandrakis and Preka-Papadema (1984) for cm wavelengths and by Klein and Trottet (1984) with emphasis at meter wavelengths. Both treated exactly the radiative transfer and used the full expressions for the emission and absorption coefficients. The magnetic field model used by Alissandrakis and Preka-Papadema was that of two opposite dipoles placed vertically below the photosphere, while Klein and Trottet used a single dipole parallel to the photosphere. The flaring loop was defined as the region between two magnetic field lines and it was assumed to be filled with a uniform and isotropic power law distribution of energetic electrons.

Similar results were obtained by both models. At short wavelengths the loop is optically thin. For a loop at the center of the disk the variation of the magnetic field and θ favour emission near the footpoints (Figure 2), while the emission of a loop away from the center of the disk is asymmetric with the primary maximum near the diskward foot. At longer wavelengths (or, equivalently, for stronger magnetic field) the loop becomes optically thick and the maximum of the emission shifts toward the top. The emission at the extraordinary mode is in general stronger than at the ordinary, but their difference decreases with optical thickness so that the ordinary mode dominates in very thick regions of the source. Alissandrakis and Preka-Papadema pointed out that the chromospheric part of the loop is unobservable at cm-λ due to the free-free absorption of ambient electrons, while Klein and Trottet found that refraction and Razin suppression can be important near the feet of loops which have their spectral maximum in the metric range. The latter also found no radical change in the loop structure for an anisotropic pitch angle distribution.

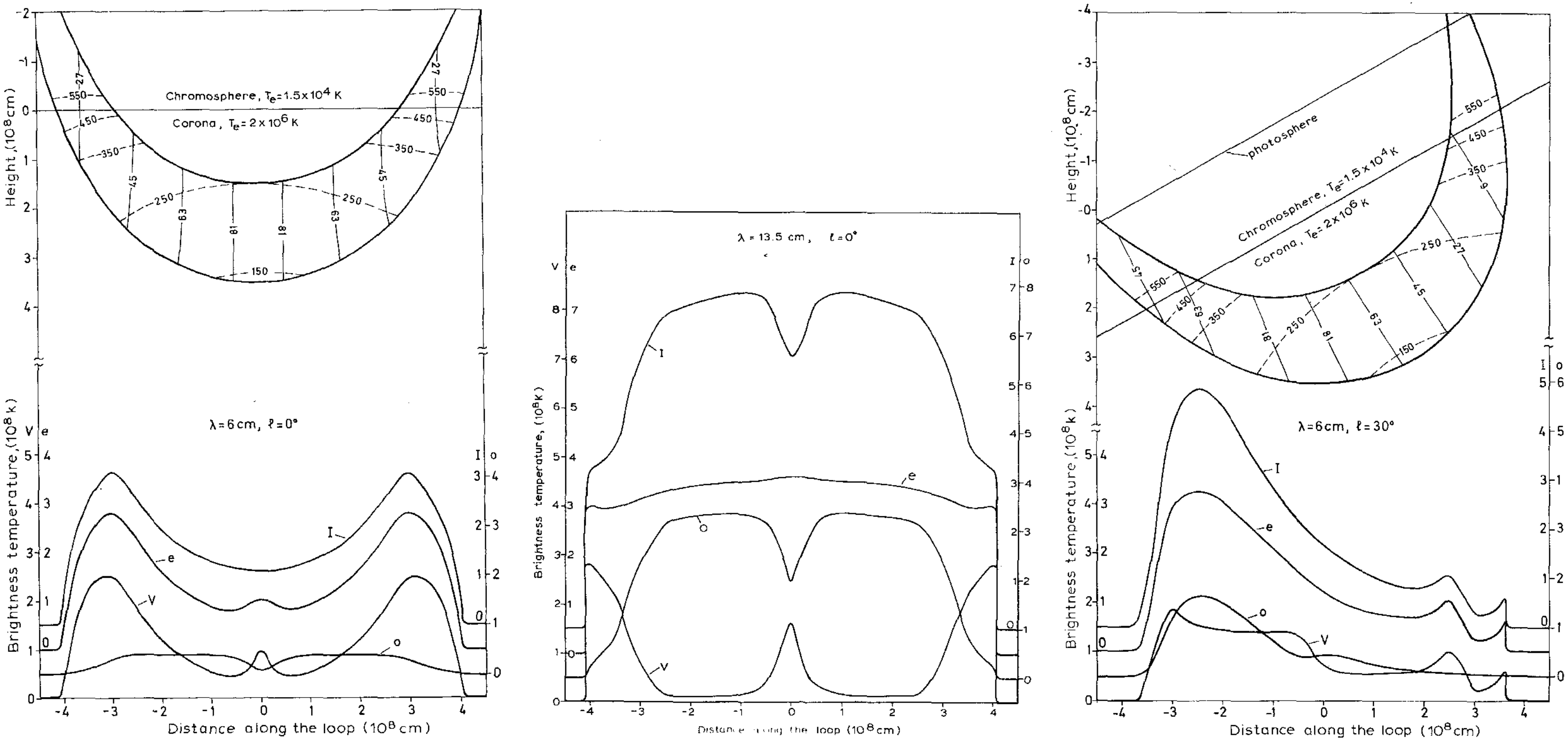

Fig. 2. Brightness temperature profiles along a loop from model computations at 6 cm, center of the disk (left), at 13.5 cm, center of the disk (middle) and at 6 cm, 30° away from the center of the disk (right). The geometry of the loop as seen by the observer is shown in the upper part of the left and right panels, with contour lines of magnetic field intensity (dashed) and the angle between the magnetic field and the line of sight (thin solid lines). The V curves show the difference of brightness temperature of the two modes. From Alissandrakis and Preka-Papadema (1984).

These model computations give a satisfactory qualitative interpretation of the basic characteristics of the elementary loop emission described in the previous section. The observation, at the same frequency, of emission peaks associated with both the top of loops and with footpoints can be due to variations of the magnetic field intensity in different loops. Moreover, the compactness of the loop is important, since in small loops a smaller variation of the magnetic field from the footpoints to the top is expected, which will favor emission from the top; in the same way, loops with large footpoint separation could give footpoint emission even at 20 cm. The computations also demonstrate the need of further multi-wavelength imaging observations, so that the variation of structure with frequency can be better established. The next step in the computations will be the detailed modeling of individual bursts, using as much observational information as possible, as has been done in the case of sunspot associated radio sources (Alissandrakis *et al.*, 1980).

5. Conclusions and Future Work

Our understanding of gyrosynchrotron emission and its application to solar radio bursts has advanced tremendously in the last 25 years, as a result of improvements in the theory, the observations and the model computations. We are now in a position to use it for more accurate diagnostics of the burst region. However this does not mean that we have exhausted the subject.

From the theoretical point of view it would be desirable to check the expressions for the emission and absorption coefficients obtained with the single particle approach with more accurate computations based on the kinetic theory, thus treating simultaneously the low temperature plasma and the energetic electrons. We should also make an effort towards a better understanding of the effects of wave coupling on the observed polarisation. So far the question has been treated qualitatively rather than quantitatively and in too simplified a magnetic field geometry compared with the real situation of a flaring loop inside a complex active region.

From the observational point of view we would like to have more multifrequency observations with high spatial resolution at cm wavelengths, in coordination with observations in other spectral regions. The extension of such observations in the mm and dm ranges is also important. We must be fully aware of the observational limitations, such as the effects of missing short baselines and we must improve the accuracy of non-radio absolute position measurements. We have not discussed here the fast time structure of microwave bursts; however, if this is not just a perturbation on top of a more gradual emission, we would have to revise a lot of our current thinking. At metric wavelengths we need a satisfactory geometrical model before proceeding to more detailed computations. To this end it is very important to continue the observations with metric–decametric radioheliographs.

Finally, we must continue the model computations of the spatial and spectral structure of bursts, integrating all observational information available. Such models should eventually include the time variation of the emission, so that we can tackle better the more fundamental problems of energy release and particle acceleration in solar flares, as well as the time evolution of a distribution of energetic particles.

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