SOLAR RADIO EMISSIONS

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Abstract

This general review covers the principal observational and theoretical interpretation of radio emissions from the Sun: 1) Streams of fast electrons and shock waves produce radio bursts in the corona and interplanetary space by the mechanism of plasma emission. 2) Fast electrons trapped in coronal magnetic loops produce bursts, sometimes by plasma emission, sometimes by gyrosynchrotron emission, and occasionally by cyclotron maser emission. 3) Coronal mass ejections (CMEs) are often associated with radio–emitting shock waves; sometimes the CME initiation preceeds an impulsive flare and the flare–initiated shock travels in the wake of the CME, and sometimes the CMEs drive shock waves in front of them. 4) Magnetic loops of CMEs may also contain thermal, nonthermal or even relativistic electrons that emit radio emission as the loops move outward.

1 Introduction

A general feature of Solar radio emissions is that the higher frequencies generally arise from closer to the Solar surface. This is because emission of a given frequency f can arise only from regions where the electron plasma frequency f_p is equal to or lower than f. Because the electron density and f_p decrease with height, the lower frequencies must thus arise from greater heights. It frequently happens that a disturbance is initiated at low heights and travels outward, generating radiation at the local plasma frequency; then a "dynamic radio spectrum" is created in which the emission drifts from high to low frequencies at a rate that depends on the speed of the disturbance, the density gradient, and whether the radiation is generated at the fundamental or the harmonic of the plasma frequency. Exceptions to this rule occur at centimeter wavelengths where the plasma level is in the chromosphere while the bursts occur in the corona, and occasionally at meter wavelengths when a confined, radio–emitting plasma/magnetic field configuration moves outward through the background corona (e.g. a moving type IV burst).

Observations of Solar radio emissions have been mainly of two kinds: 1) Measurements of burst spectra are made with dynamic spectrographs. In addition to the flux density, some spectrographs also measure the degree of circular polarization of the emission.

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Normally the radiation from the entire Sun is recorded using wide–beamwidth antennas, so that multiple or moving sources, if they exist, cannot be identified, source sizes cannot be measured, and hence brightness temperatures cannot be deduced. Spectrographs in space are of this type, usually using electrically short dipoles. For certain kinds of bursts, the outward motion of the exciting agent (electron streams or shocks) can be deduced from the drift of frequency with time together with an appropriate model of the coronal/interplanetary density. 2) Measurements of source position, structure, size, flux density, brightness temperature and polarization are made with imaging instruments such as radioheliographs and general purpose aperture synthesis telescopes.

Dynamic spectrograms are essential for identifying the types of bursts that result from a Solar eruption, and hence the exciting mechanism. Imaging instruments complement the spectrographs to make the measurements more quantitative.

The following table summarizes some of the important parameters of Solar radio emissions.

	Wavelengths	Brightness temperature	Emission mechanism
Quiet Sun	sub-mm-DAM	$\lesssim 10^4$ - 10^6 K	bremsstrahlung
Active regions	sub-mm-DAM	10^4 - 3×10^6 K	bremsstrahlung
	centimeter	1-3 $\times 10^6$ K	gyroresonance
Flares	mm - m	10^6 - 10^{10} K	gyrosynchrotron
	cm - dm	to 10^{15} K	cyclotron maser
	dm - km	to 10^{17} K	plasma radiation

In this communication I concentrate on long–wavelength radio emissions from Solar flares and say little or nothing about the bremsstrahlung radiation of the quiet Sun, the gyroresonance radiation from strong magnetic fields near sunspots, or the gyrosynchrotron radiation at centimeter wavelengths that originates in the low corona. Reviews of these subjects have been given in the books of McLean and Labrum [1985] and Benz [1993], and articles by Dulk [1985] and Bastian et al. [1996, 1998].

1.1 Distinguishing characteristics of emission mechanisms

There are four emission mechanisms that are believed to produce the various radio phenomena observed, two of them are incoherent mechanisms: thermal bremsstrahlung and gyrosynchrotron, and two coherent mechanisms: cyclotron maser and plasma radiation. Gyrosynchrotron radiation includes gyroresonance radiation when the electron energies are non–relativistic, and synchrotron radiation when they are strongly relativistic.

The following table gives characteristics of these four emission mechanisms that usually enable them to be identified.

Mechanism	Source size	T_B or T_{eff}	Circular polarization	Time variability
Thermal bremsstrahlung	large $R \lesssim R_O$	low $\lesssim 10^6$ K	low near zero	low $\gtrsim$ days
Gyro- synchrotron	moderate $R < R_O$	moderate $\lesssim 10^{10}$ K	moderate $\lesssim 30\%$	moderate min to hr
Cyclotron maser (f $\gtrsim$ 1 GHz)	small $R \ll R_O$	high to 10^{15} K	often high to 100%	high ms to s (spikes) hr (outbursts)
Plasma radiation (f $\lesssim$ 1 GHz)	small $R \ll R_O$	high to 10^{17} K	mod. to high 10% to 90%	high s to min (bursts) days (outbursts)

2 Radio bursts from Solar flares

In their classic review, Wild et al. [1963] introduced idealized dynamic spectra of flare-associated radio bursts, showing the relationship among microwave bursts and decimeter/meter wave bursts of types I to V. In addition, they developed an elegant formulation of fundamental relationships among specific intensity, brightness temperature, effective temperature of radiating electrons, and flux density. An updated version of an idealized dynamic spectrum is contained in the review by Dulk [1985].

2.1 Dynamic spectrum of November 4, 1997

Figure 1 is an example of a dynamic spectrum containing several kinds of bursts. The spectrum covers about 4.5 orders of magnitude of frequency (about the same ratio as from X–rays to infrared). In terms of Solar radii, the bursts shown in the figure occurred at all altitudes from ~ 1000 km above the surface to ~ 100 R_O. The right–hand ordinate scale gives an indication of where the various emissions arose; this scale is based on fundamental plasma radiation using the coronal/solar wind density model of Leblanc et al. [1998] augmented to match the actual density at 1 AU at the time of the event.

Following a weak precursor type III burst at 0557 UT, drifting from about 50 to 1 MHz in 2 min, a group of very intense type III bursts drifts from about 200 to 0.1 MHz (1.1 to 70 R_O) in about 30 min. At later times the group of type IIIs extends down to 20 kHz, near the plasma frequency at 1 AU. Within a minute of the initiation of the type III bursts a microwave impulsive burst commences, covering the range from more than 1000 to less than 200 MHz. At about 0600 UT a type II burst begins: Both fundamental and harmonic components are visible, the fundamental drifting from about 50 to 5 MHz between 0600 and 0620 UT (the later part is most easily distinguishable). The harmonic drifts from about 150 to 20 MHz between about 0600 and 0615 UT.

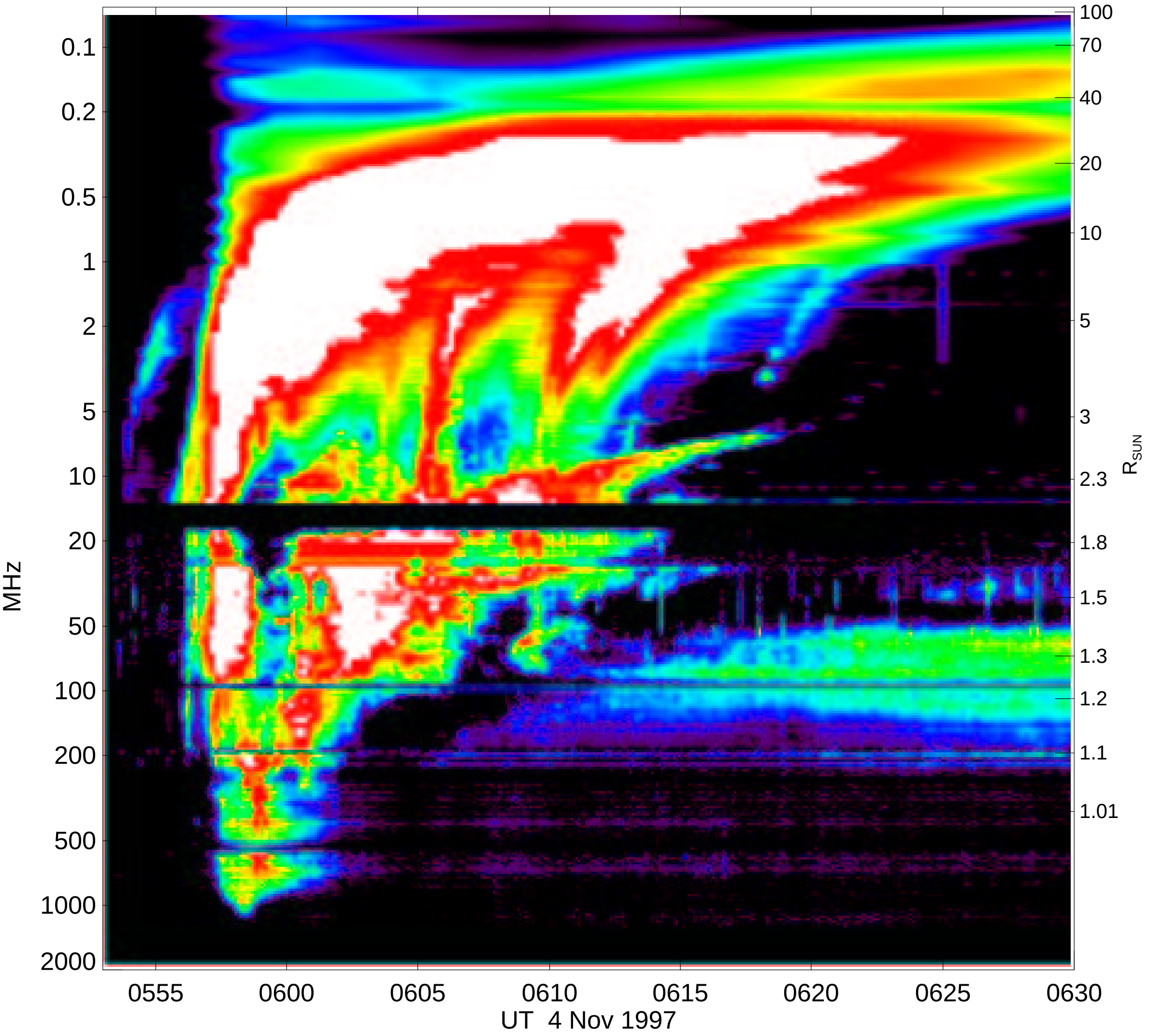

Figure 1: Dynamic spectrum of the Solar event of November 4, 1997, showing weak, precursor type III bursts, an intense group of type IIIs, a microwave impulsive burst, a type II with fundamental and harmonic components, shock–accelerated type IIIs emanating from the type II burst, and type IV (flare continuum) radiation. The range 1800 to 18 MHz was recorded by the spectrograph at Culgoora [Prestage et al., 1994] and the range below 13.8 MHz was recorded by the WAVES instrument on the Wind spacecraft [Bougeret et al., 1995]. A CME was associated with this event, and an interplanetary shock wave was recorded at 1 AU on Nov. 6 at 2220 UT.

Emanating from the type II bursts between about 0602 and 0620 UT, the spectrum contains a series of type III bursts that proceed rapidly to lower frequencies, merging at about 1 MHz with the original type III group from the lower corona. These are "shock–accelerated type III bursts"; they are described in detail by Dulk et al. [2001], and the merged event below 1 or 2 MHz is what Cane et al. [1981] originally described as a "shock–accelerated event". The shock–accelerated type III bursts demonstrate forcibly that the shock wave not only produces a slowly–drifting type II burst, but it also accelerates electrons to speeds of 0.1–0.3 c that travel outward from the shock, often to 1 AU.

Following the type II burst in the meter wavelength range, a band of continuum emission is visible between 200 and 30 MHz. This "type IV" or "flare continuum" radiation is produced by electrons trapped in stationary or slowly moving coronal loops. The association with the type II burst and the similar slope of commencement suggest that the radiating electrons were accelerated by the shock wave to energies of a few keV and were trapped in magnetic loops where they emitted plasma radiation for periods of $\gtrsim 1$ hour [e.g. Robinson, 1985].

Most of the bursts, type III, shock–accelerated type III, type II, and flare continuum, are convincingly attributed to plasma radiation. The microwave impulsive burst is due to gyrosynchrotron radiation.

3 Flares, shock waves, CMEs and geomagnetic disturbances

Until a few years ago, shock waves initiated by the energy of impulsive flares were believed to travel to 1 AU, impinge on the Earth's magnetosphere, and cause geomagnetic storms and aurorae. However, it is now widely accepted that coronal mass ejections (CMEs) and the shocks driven by them are the primary agent causing geomagnetic storms. There is no consensus as to the relationship among flare–initiated shock waves (blast waves?), type II radio bursts, CMEs, and interplanetary shocks (piston–driven waves?) impinging on Earth.

The conclusions of a recent study of 10 flare/shock/CME events by Leblanc et al. [2001] are summarized as follows:

- Type II initiation usually occurs after the liftoff of the CME.

- Type II burst sources at $\lesssim 30\ R_O$ usually progress outward behind the front of the CME, most clearly, behind the estimated radial progression of the CME.

- These observations strongly imply that type II shocks in the corona are usually blast waves related to impulsive energy release by the flare.

- Type II burst sources usually lie close to the trace connecting the flare to the shock arrival at 1 AU. At $\lesssim 30\ R_O$ the sources are lower than the fronts of CMEs.

- The CMEs studied usually decelerate in the observed range of $\lesssim 30\ R_O$. Thus at some (unknown) radial distance their speeds and positions are aligned with the trace of the shock from the flare to 1 AU.

- From that radial distance onward, the interplanetary shock is piston driven by the CME.

- However, in some events, the CME liftoff and type II initiation are essentially simultaneous, and the CME and type II progressions are essentially the same. Thus the shock waves may be driven by the CMEs all the way from 1 R_O to 1 AU.

- And, for some events, it cannot be excluded from present observations that the shock is a blast wave from the flare to 1 AU.

4 Radio emission from a CME

A convincing observation of radio emission from outward–moving CME loops was recently reported by Bastian et al. [2001]. After achieving a large dynamic range in observations by the Nançay radioheliograph, a large loop–like structure was evident at 164 and 237 MHz that proceeded outward to a radial distance of about 3.4 R_O. Its progression was essentially superimposed on the trace of the leading, bright loop of a CME as determined from a series of images by the LASCO coronagraph.

From the spectrum of the radio sources resolved by the radioheliograph (164 and 237 MHz from the entire loop, plus 327 and 432 MHz from the lower parts), Bastian et al. deduced that the emission was due to synchrotron radiation from electrons of energy 0.5 to 5 MeV trapped in a magnetic field of 0.1 to a few G embedded in the CME loops. A type II burst and shock–accelerated type III bursts were observed contemporaneously by ground and space–based spectrographs. This circumstantial evidence, and the lack of any evidence of acceleration elsewhere, led the authors to suggest that the most likely acceleration region for the relativistic electrons was the shock wave associated with the fast–moving CME.

To date, Bale et al. [1999] have given the only report of in–situ observations of electrons accelerated by an interplanetary shock that produced a type II burst. In the event reported by them, no observations existed of electrons of energy greater than 1.14 keV.

The event of Bastian et al. comprises the best evidence so far uncovered (even though circumstantial) of electrons accelerated to MeV energies by a shock wave in the corona, and in particular where the radio source was closely associated with a fast–moving CME. Other authors, starting with Boischot and Denisse [1957], have suggested synchrotron radiation as the mechanism producing the “moving type IV bursts” discovered by Boischot [1957]. A detailed model of gyrosynchrotron radiation from moving and expanding sources, including betatron deceleration and Razin suppression, was developed by Dulk [1973]. Later work challenged the synchrotron model, arguing that some observations require the emission to be coherent, and suggesting that plasma radiation is the relevant emission mechanism [e.g. review by Stewart, 1985]. Unfortunately, unlike the event of Bastian et al. [2001], none of the observations of moving type IV sources could be directly related to shock waves or loops of CMEs.

5 Conclusion

What have we learned?

Although some controversy remains, the observations and theory of type III bursts are generally in good shape. We know the properties of the exciting electrons, the Langmuir waves, and the radio waves. Density irregularities probably play an important role [e.g. Robinson and Cairns, 2000].

The acceleration of electron streams by shock waves is now known to produce shock–accelerated (SA) type III bursts, clarifying what is an “SA Event”.

The relationship among flares, type II bursts, shock waves in the corona, CMEs, and shock waves near 1 AU, is being clarified; however much more careful analysis remains to be done.

What have we yet to learn?

Although not developed in this review, important questions remain regarding the radio radiation of the quiet chromosphere and corona [e.g. Bastian et al., 1996]: Why is it less bright than predicted by existing models of density and temperature as a function of altitude? What is the role of inhomogeneities in density and magnetic field on very small scales?

How is radio radiation generated by shock waves, i.e. type II bursts and SA type III bursts? What is the electron distribution near shocks? Do these processes differ between quasi–parallel and quasi–perpendicular shocks? What are the properties of the Langmuir waves and their conversion to type II radio bursts? Can theories such as stochastic growth explain the observations?

References

Bale, S. D., M. J. Reiner, J.–L. Bougeret, M. L. Kaiser, S. Krucker, and D. E. Larson, The source region of an interplanetary type II burst, *Geophys. Res. Lett.*, **26**, 1573, 1999.

Bastian, T. S., G. A. Dulk, and Y. Leblanc, High resolution microwave observations of the quiet Solar chromosphere, *Astrophys. J.*, **473**, 539, 1996.

Bastian, T. S., A. O. Benz, and D. E. Gary, Radio emission from Solar flares, *Ann. Rev. Astron. Astrophys.*, **36**, 131, 1998.

Bastian, T. S., A. Vourlidas, M. Pick, D. Maia, and A. Kerdraon, Radio emission from coronal mass ejections, presented at European Geophysical Society, Nice, France, 2001.

Benz, A., *Plasma Astrophysics: Kinetic Processes in Solar and Stellar Coronae*, Dordrecht: Kluwer, 1993.

Boischot, A., Caractères d'un type d'émission hertzienne associé à certaines éruptions chromoshériques, *Comptes Rendu Acad. Sci.*, **244**, 1326, 1957.

Boischot, A., and J. F. Denisse, Les émissions de type IV et l'origine des rayons cosmiques associés aux éruptions chromosphériques, *Compte Rendu Acad. Sci.*, **245**, 2194, 1957.

Bougeret, J.–L., M. L. Kaiser, P. J. Kellogg, R. Manning, K. Goetz, S. J. Monson, N. Monge, L. Friel, C. A. Meetre, C. Perche, L. Sitruk, and S. Hoang, Waves: The radio and plasma wave investigation on the WIND spacecraft, *Space Sci. Rev.*, **71**, 231, 1995.

Cane, H. V., R. G. Stone, J. Fainberg, R. T. Stewart, J.–L. Steinberg, and S. Hoang, Radio evidence for shock acceleration of electrons in the Solar corona, *Geophys. Res. Lett.*, **8**, 1285, 1981.

Dulk, G. A., The gyro–synchrotron radiation from moving type IV sources in the Solar corona, *Solar Phys.*, **32**, 491, 1973.

Dulk, G. A., Radio emission from the sun and stars, *Ann. Rev. Astron. Astrophys.*, **23**, 169, 1985.

Dulk, G. A., Y. Leblanc, T. S. Bastian, and J.–L. Bougeret, Acceleration of electrons at type II shock fronts and production of type III–like bursts, *J. Geophys. Res.*, **105**, 27343–27352, 2000.

Leblanc, Y., G. A. Dulk, and J.–L. Bougeret, Tracing the electron density from the corona to 1 AU, *Solar Phys.*, **183**, 165, 1998.

Leblanc, Y., G. A. Dulk, A. Vourlidas, and J.–L. Bougeret, Tracing shock waves from the corona to 1 AU, *J. Geophys. Res.*, **105**, in press, 2001.

McLean, D. J., and N. R. Labrum (editors), Solar Radiophysics, Cambridge, UK: Cambridge Univ. Press, 1985.

Prestage, N. P., R. G. Luckhurst, B. R. Paterson, C. S. Bevins, and C. G. Yuile, A new radiospectrograph at Culgoora, *Solar Phys.*, **150**, 393, 1994.

Robinson, R. D., Flare continuum, Chap. 15 in *Solar Radiophysics*, edited by D. J. McLean, and N. R. Labrum, Cambridge, UK: Cambridge Univ. Press, p. 385, 1985.

Robinson, P. A., and I. H. Cairns, Theory of type III and type II Solar radio emission, *Radio Astronomy at Long Wavelengths in Geophysical Monograph 119*, edited by R. Stone, E. Weiler, and M. Goldstein, American Geophysical Union, 37, 2000.

Stewart, R. T., Moving type IV bursts, Chap. 14 in *Solar Radiophysics*, eds. D. J. McLean, and N. R. Labrum, Cambridge, UK: Cambridge Univ. Press, p. 361, 1985.

Wild, J. P., S. F. Smerd, and A. A. Weiss, Solar bursts, *Ann. Rev. Astron. Astrophys.*, **1**, 291, 1963.