IX. SOLAR RADIO EMISSION

Millimeter and Microwave Activity of the Sun

M. R. Kundu and S. M. White
Astronomy Program
University of Maryland, College Park, MD

Abstract

The emission of solar flares at millimeter wavelengths is of great interest both in its own right and because it is generated by the energetic electrons which also emit gamma rays. Since high-resolution imaging at gamma-ray energies is not presently possible, millimeter observations can act as a substitute. Except for that class of flares known as gamma-ray flares the millimetric emission is optically thin. It can be used as a powerful diagnostic of the energy distribution of electrons in solar flares and its evolution, and of the magnetic field. We have carried out high-spatial-resolution millimeter observations of solar flares this year using the Berkeley-Illinois-Maryland Array (BIMA), and report on the preliminary results in this paper (Kundu et al 1990; White et al 1990). We also report some recent results obtained from multifrequency observations using the VLA (White et al 1990).

Millimeter Bursts

Most millimeter-wave observations of solar flares have been hampered both by poor spatial resolution (because of the lack of synthesis interferometers) and by poor sensitivity (since the flux from the Sun's thermal emission is so high at millimeter wavelengths). The number of reported observations of bursts at millimeter wavelengths is relatively small, and there are none for which true imaging data have been reported.

The BIMA array, presently consisting of three antennas but being expanded to six to produce an aperture synthesis imaging instrument with 15 baselines, has a spatial resolution of $\gtrsim$ 1" arc, and time resolution as good as 0.3 sec. In its present configuration there are too few baselines to image rapidly time-variable phenomena on the Sun, but the range of spacings available at BIMA (2" - 60") is ideal for the study of flare sources; with data from three baselines we can determine the spatial scales involved and study the time evolution at high sensitivity and resolution. If good phase information is available, we can in principle obtain positions of burst sources.

E. R. Priest and V. Krishan (eds.), Basic Plasma Processes on the Sun, 457–465.

In March 1989 an extremely productive solar active region crossed the disk of the Sun and produced numerous large flares. At short notice the array was used to track this active region during daylight hours. The array was in a wide configuration with interferometer fringe spacings from 2" - 5", and due to maintenance work only one baseline was available much of the time. Using sidereal observing programs the best available time resolution was 10 seconds. We observed over 15 flares at ~ 86 GHz during the observing period, ranging from sub-flares to the largest class of flares (GOES soft-X-ray class "X"). Examples of these are shown in Figure 1.

Our sensitivity is about 0.01 - 0.02 sfu. Note that the patrol telescopes in Bern and Nobeyama presently operating at these wavelengths have sensitivities of 10 sfu at best. Thus the BIMA observations are roughly 1000 times more sensitive, and provide spatial scale and phase information as well. Subsequently for solar observations we were able to use a much better time resolution available (0.32 seconds) and in addition obtain total power information to supplement the correlated amplitudes. The high-time-resolution mode was used during an international campaign in June of 1989, and again a number of flares were detected. Examples of these are given in Figure 2.

We present the time profiles of several bursts during the March period in Fig. 1. The vertical axis in this figure is in solar flux units, while the horizontal axis is in UT hours. The time axes are all on the same scale. This figure clearly illustrates that while most of the bursts were impulsive and short-lived, we also saw a number of longer duration bursts.

All the bursts are fairly weak, with none exceeding 1 sfu of correlated amplitude. A number have rise times less than the available resolution of 10 seconds. Due to the short fringe spacing (generally about 4", i.e. sensitive only to structures which are smaller than 2"), we believe that in a number of these bursts the correlated flux is well below the total power radiated. This is particularly true for the longer duration bursts, which generally have larger source sizes, and we believe that the spiky profiles of the longer bursts are evidence that they are over-resolved.

On occasions when we were able to use three baselines we found that sometimes the shortest baseline was seeing much greater flux than the longer baselines, and therefore the spatial scale of the burst is believed to be longer than the largest resolution available (about 2" here). However, there are bursts for which there is evidence for a complicated asymmetry, such that the shortest baseline does not see the largest flux at all times.

The flares shown in Fig. 2(a) and Fig. 2(b) (White et al 1990) were observed on June 23 and June 24, 1989 using .32 second time resolution. The vertical axis is in arbitrary units (the peak flux is about 1 sfu), and the horizontal axis is in UT seconds. The time profile is that of a simple impulsive microwave burst. The rise time is resolved: in the 5.7 second duration of the rise (start-to-peak) are some 19 data points. The decay appears to be exponential. The solid line on the figure is the correlated flux (good phase measurements were obtained but are not shown here). The smooth profile suggests that the source structure is very

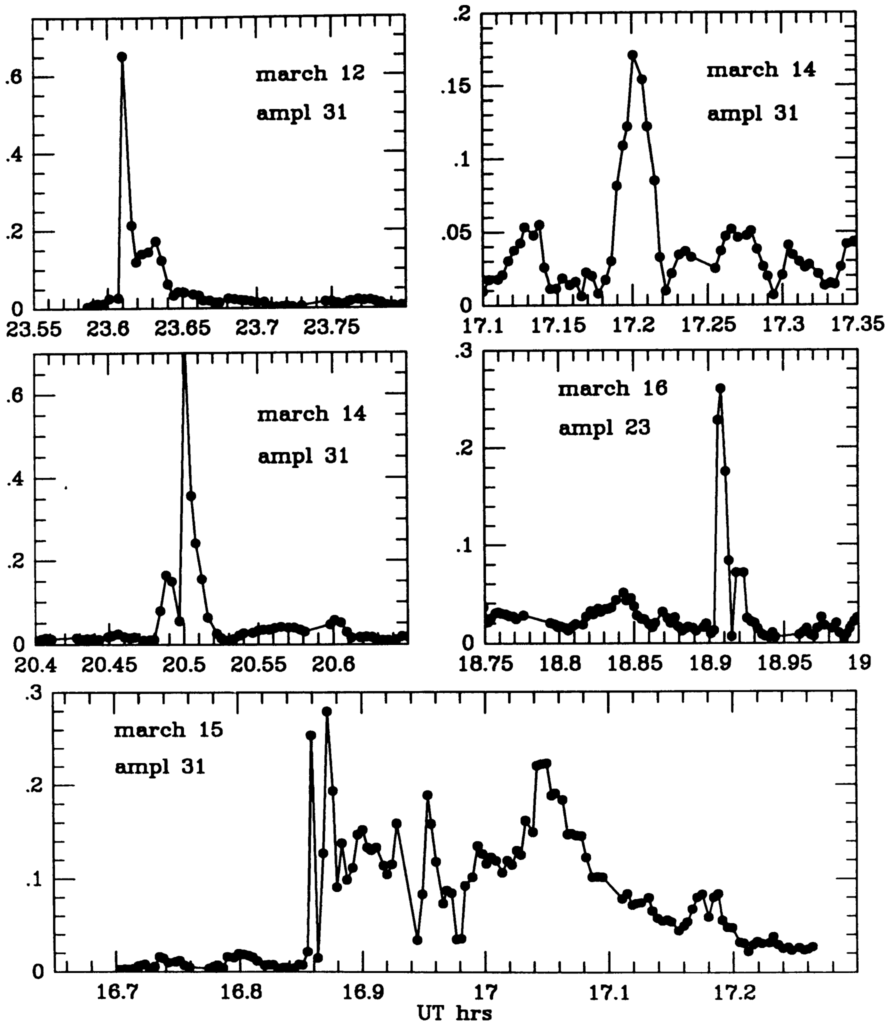

Figure 1 Time profiles of some 89 GHz bursts observed in March 1989 (from Kundu et al 1990). See text for details.

https://doi.org/10.1017/S007418090008846X Published online by Cambridge University Press

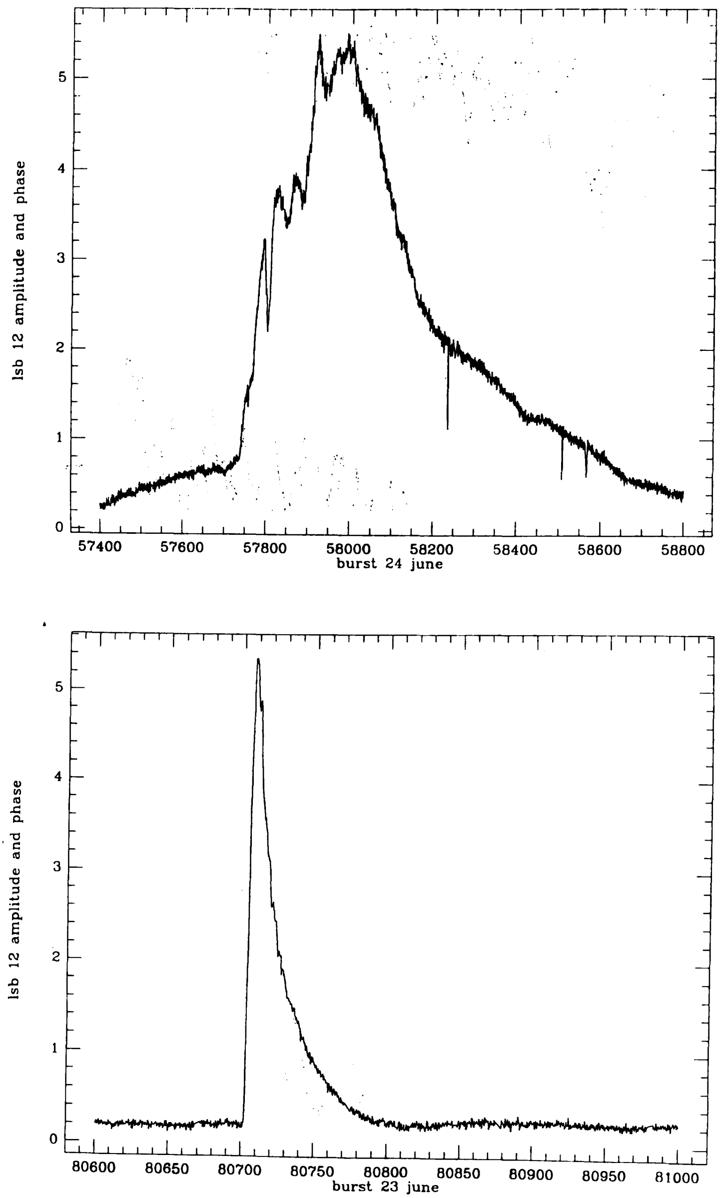

Figure 2 Time profiles of an impulsive flare (top) and long duration flare (bottom) observed in June 1989 with 0.32 sec time resolution (from White et al 1990a). See text for details.

simple, and that all the flux is resolved. This makes the source size about 5 arc seconds or smaller.

By contrast with the impulsive flare shown in Fig. 2(a) the June 24 event (Fig. 2(b) shows a gradual rise and emission continuing for 20 minutes. On the basis of the smooth profile we again argue that most of the flux is being seen by the interferometer, and therefore the burst source is smaller than ~ 4 arc seconds. The relative stability of the phase measurements (not shown here) are further evidence for this.

One important conclusion that emerges from our March 1989 observations is that the millimeter bursts cannot be thermal emission. Any thermal gyrosynchrotron spectrum would be well below our detection threshold at these high frequencies, because thermal emission falls off roughly as f^{-8}. The spectral indices implied by the March detections are in the range -3 to -5.

Comparing the March observations, with long baselines, and the June observations with a shorter baseline, we conclude that typical source sizes at 89 GHz are in the range 2 - 5 arcseconds.

Flares such as that in Figure 2(b), if all the emission is due to energetic particles, clearly imply particle acceleration continuing throughout the flare.

The rather long bursts with many spikes such as that shown in Fig. 1 (event of March 14) are over-resolved. This implies that the spikes are not due to genuine time variation, but rather due to spatial scales; sequential brightening of many flaring kernels will manifest itself as time structure. Similar behavior is sometimes observed in Hα.

Microwave Activity

During the International solar month (September 1988) we observed the Sun with the Very Large Array (VLA) on four days in the period September 11-17. The VLA was in its most compact configuratiaon (D). which is ideal for studying large scale coronal structures, although with relatively poor resolution (40 arc sec at 1.5 GHz, 3 arc min at 0.33 GHz, 15 arc sec at 5 GHz, 10 arc sec at 8.4 GHz and 5 arc sec at 15 GHz). The data are being used for several studies. The White et al paper in this volume discusses some large scale features using the full Sun disk pictures at 1.5 GHz and 0.333 GHz. At higher frequencies we do not have full disk pictures. However, several active regions were mapped quasi-simultaneously at both higher (5-15 GHz) and lower (1.5 - 0.333 GHz) frequencies.

The most striking result that has come out of these observations is that there is exceptionally good correspondence between the 1.5 GHz radio sources and the regions which are dark in He 10830 images and bright in Ca images. Dark regions in the He 10830 images indicate the presence of hot material in the corona. Even very small weak features in the radio maps appear to be associated with dark regions on He images. A set of four full-disk pictures at 1.5 GHz is shown in the paper by White et al in this issue. Using the observations at 5 different frequencies it is possible to construct a 3-dimensional picture of the solar atmosphere above an active region. Figure 3 shows an example of such 3-dimensional picture. It should be noted while the regions at 15 to 1.5 GHz are quiet

https://doi.org/10.1017/S007418090008846X Published online by Cambridge University Press

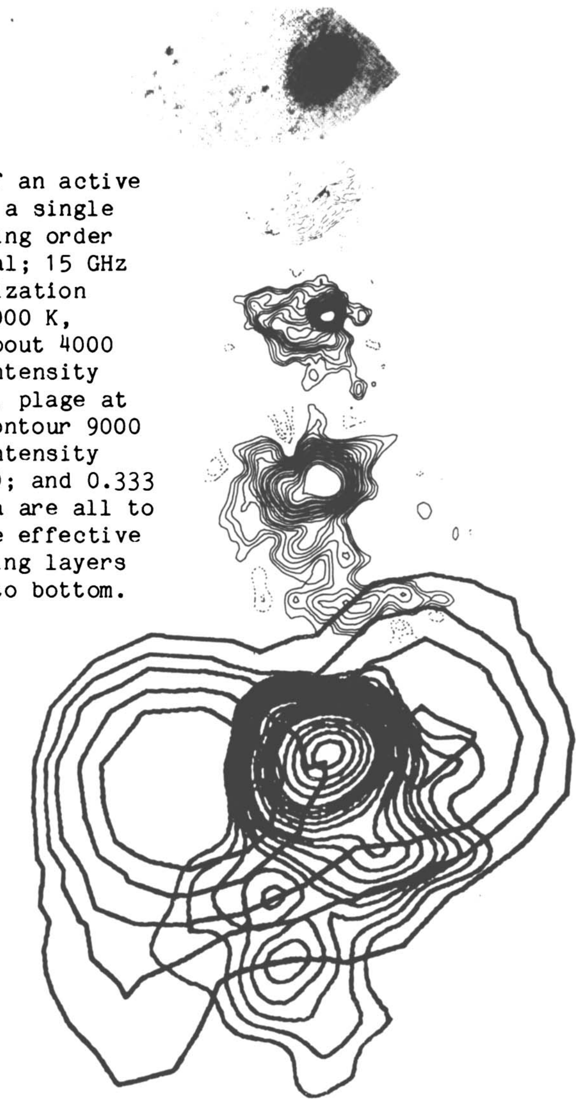

Figure 3. Images of an active region dominated by a single spot, in the following order from the top: optical; 15 GHz left circular polarization (plage at about 30,000 K, bottom contour at about 4000 K); 8.4 GHz total intensity (peak 2.8 million K, plage at 800,000 K, bottom contour 9000 K); 1.5 GHz total intensity (peak 1.8 million K); and 0.333 GHz. The radio data are all to the same scale. The effective height of the emitting layers increases from top to bottom.

https://doi.org/10.1017/S007418090008846X Published online by Cambridge University Press

active regions, the region at 0.333 GHz is a weak storm center. The 15 GHz map shows only left circular polarization: the right circular polarization map shows a point source at the location of the left-hand peak, but twenty times as strong.

Studies of three-dimensional structures of active region have been done in the past by Shevgaonkar and Kundu (1984) using the VLA at 15, 5 and 1.5 GHz. The main results of these studies indicated that the radiation at 2 cm is dominated by thermal bremsstrahlung even in the case where the observed degree of polarization is very high, ~ 80%. The radiation at 6 cm is always due to optically thick gyroresonance absorption, whereas 20 cm radiation could be either due to gyroresonance absorption or due to optically thin thermal bremsstrahlung, depending upon the observed brightness temperature. If T_B is $\lesssim 10^6$ K, the thermal bremsstrahlung mechanism dominates, but for $T_B \gtrsim 2 \times 10^6$ K, the radiation is due to gyroresonance absorption.

At 6 and 3.3 cm the peak brightness temperature probably corresponds to the x mode being optically thick at the third gyroresonance harmonic. The peak brightness temperature at these frequencies represent the temperature in the layers where the magnetic field is 600 and 1000 gauss, respectively. The temperature drops as we go out (up in wavelength) from 3.3 cm to 20 cm, implying that at different frequencies we are looking at different loop structures. In this case the lower-lying loops (those at 3.3 cm) have the greatest temperature. At the higher frequencies we can clearly distinguish between a spot source and the "plage" source associated with the active region trailing the spot, but at 6 and 20 cm it is difficult to do so, because the plage emission is probably free-free and its brightness temperature increases rapidly with wavelength, while the gyroresonance emission from the spot decreases. Thus the relative contributions of "spot" and "plage" sources to the slowly varying continuum is a strong function of frequency.

Our studies are based upon 5 frequency observations and as such we have the possibility of observing much more details as a function of height. This structure is obviously related to the structural details of loops and therefore of magnetic fields between the heights of ~ 5,000 to 100,000 km above the photosphere.

This research was supported by NSF grant ATM 87-17157 and NASA grant NAG-W-1541.

References

Kundu, M.R., White, S.M., Gopalswamy, N., Bieging, J.H. and Hurford, G., 1990, Ap. J. Letters (submitted).

Shevgaonkar, R.K. and Kundu, M.R., 1984, Astrophys. J., **283**, 413.

White, S.M., Kundu, M.R., and Bieging, J.H., 1990a, in preparation.

White, S.M., Kundu, M.R., Gopalswamy, N., and Schmahl, E.J., 1990b, in this issue.

DISCUSSION

SMITH: As you probably know the 1-10 MeV range is not very good for mm waves as a proxy for γ-rays, because in this range there is a major component due to excitation of trace elements by protons and it is impossible to separate this component from the bremsstrahling component due to electrons. Is there any hope of extending the observations to > 10 MeV where we know that the γ-rays are due solely to electrons?

KUNDU: We can probably go to ~ 1.2 mm - even there with reasonable magnetic fields in flaring regions, the electron energy required for mm emission will be of the order of 1 MeV. However, we can test other effects of γ-ray flares, for example anisotropy (limb excess of γ-ray flares in contrast to disk distribution). If we find a similar effect, then we shall be on solid ground regarding mm bursts as a proxy for γ-ray bursts. If we do not find such an anisotropy, then we shall have to deal with different mechanisms to explain γ-ray anisotropy.

ALURKAR: (i) For the over-resolved burst event, what was the spatial separation of the burst structure?
(ii) What is the possibility that the observed structure is a temporal variation of the burst radiation?

KUNDU: (i) Spatial separation of individual burst source structures cannot be determined with the present system. At present all we can say is that there are several structures each of order 1 arcsec within the overall burst source.
(ii) If there is no phase jump associated with spikes, I shall consider the time structures as genuine time structures.

STEPANOV: What is the origin of superthermal electrons in moving type IV source?

KUNDU: There may be several possible origins of nonthermal particles for type IV: reconnections taking place driving the onset of a CME or an accompanying flare; shock waves piston-driven by a CME; or a blast wave generated by the flare explosion accompanying the CME. If you are referring to slow-mode shock acceleration of particles responsible for slow type IV's associated with slow CME's, I really do not know the answer. However, in the paper on the February 17, 1985 CME event (*Ap.J*, in press 1989), we suggested current-driven lower-hybrid waves, which can operate at both fast and slow shocks, as the source of the energetic electrons for a moving type IV burst.

VERMA: It was found that some flares show that low-frequency microwave (mw) bursts start earlier than the high-frequency mw bursts and some flares show the reverse. Please explain the reason for the same.

KUNDU: It is possible to explain the relative delay between low-frequency, high-frequency microwave bursts and hard X-ray bursts by a combination of Joule heating and an acceleration mechanism (for details, see G. Holman,*Ap.J*,1985).

KALKOFEN: Radiation at mm wave lengths is also emitted from the middle chromosphere. The radiation is due to free-free transitions of H^-, with the source function given by the Rayleigh-Jeans function in LTE. Would you comment on a periodic signal and on the magnitude of the temperature fluctuations?

KUNDU: The non-flare mm emission is certainly due to free-free transition. The emission from quiet regions appears to have some quasi-periodicity, with a period of about 180 sec. Searches for other periods using single dish observations have so far not been successful. The problem has to be attacked again using interferometric observations.

https://doi.org/10.1017/S007418090008846X Published online by Cambridge University Press