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Nonthermal Flare Emission from MeV-energy Electrons at 17, 34 and 86 GHz

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Abstract. We present analyses of two solar flares observed with high spatial resolution at 86 GHz with the BIMA millimeter–wavelength telescope and at 17 and 34 GHz with the Nobeyama radioheliograph. In both events there is evidence for a simple bipolar structure in the radio source: in one case two distinct sources are clearly spatially resolved, while in the second the polarization image at 17 GHz suggests a bipolar nature. Bipolar sources are expected of MeV–energy electrons trapped in loop structures.

1. Introduction

Over the past several years we have demonstrated with the BIMA interferometer that millimeter wavelength observations can be used to study the production of electrons with energies of order 1 MeV and higher in "ordinary" solar flares. This is because the gyrosynchrotron emission of relatively small numbers of nonthermal MeV–energy electrons can be detected rather easily with millimeter–wavelength interferometers. In this paper we present two events which have been imaged both by the BIMA millimeter interferometer at 86 GHz and by the Nobeyama radioheliograph (NRH) at 17 and 34 GHz. The two telescopes have similar resolution (here $10'' - 12''$). The importance of having images at such high frequencies is that the high–frequency radio spectrum can be reliably determined for different structures within the flare source. The two events discussed here have quite contrasting properties and are used to investigate the acceleration of energetic electrons in solar flares.

2. Event of 1998 November 24

This was a winter event occurring at 23:42 UT: the Sun was at 8° elevation at BIMA at the time and was low on the eastern horizon at Nobeyama. The GOES

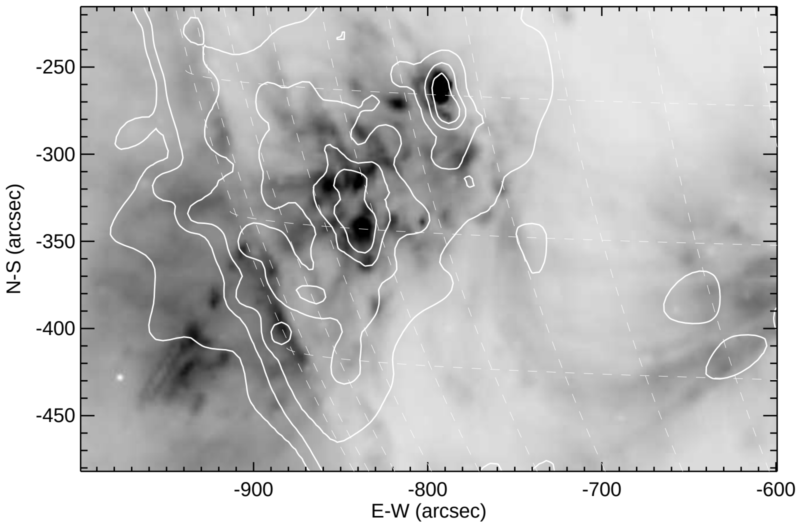

Figure 1. Overlay of contours of 17 GHz emission at 23:43:20 UT on an EIT 195Å image taken at 23:48:10 UT on 1998 November 24. The 17 GHz contours are plotted at brightness temperature levels of 3300, 6600, 13300, 20000, 33200 and 46500 K. Most of the emission is non–flaring: the flare location is the bright source at (-795″,-265″).

class of this event was C2.9 and it occurred at heliographic coordinates S16E57. Figure 1 shows an EIT 195Å image of the post–flare stage, some 6 minutes after the GOES soft X–ray peak, with 17 GHz radio contours overlaid: the flare site is the compact dark feature in the upper middle of the panel. The post–flare 195Å source has a dimension of order 15″, while the radio source is somewhat larger.

Figure 2 shows radio and soft X–ray time profiles for the event. The microwave data show very spiky time profiles and a very brief duration. The soft X–ray profile shows several stages: a preflare rise at 23:40:00, a steeper rise from 23:40:20 to 23:40:45, a more gradual rise from 23:40:45 (when the bright microwave peaks begin) to the GOES peak at 23:42:20, and then a steady decay. From the microwave fluxes it appears that this event had a low–frequency spectral peak (between 4 and 9 GHz); the flux at 17 GHz is small although the time profile matches that of the lower frequencies. At 86 GHz the BIMA data show a more gradual time profile and a peak flux considerably stronger than at 17 GHz, but the time of the 86 GHz peak matches that of the 17 GHz peak. The 86 GHz time profile does not match the GOES time profile, so the 86 GHz emission from this event does not appear to be purely thermal free–free emission from the soft X–ray–emitting plasma as in some other events (Kundu et al. 1994). The event was not detected at 34 GHz.

17 GHz and 86 GHz images of the flare are shown in Figure 3. The weather at BIMA was poor for millimeter observing on this particular day, and with the source at such a low elevation we would not place too much significance on the bipolar structure found by self–calibrating the 86 GHz data were it not for the fact that the 17 GHz NRH images with similar resaolution also show

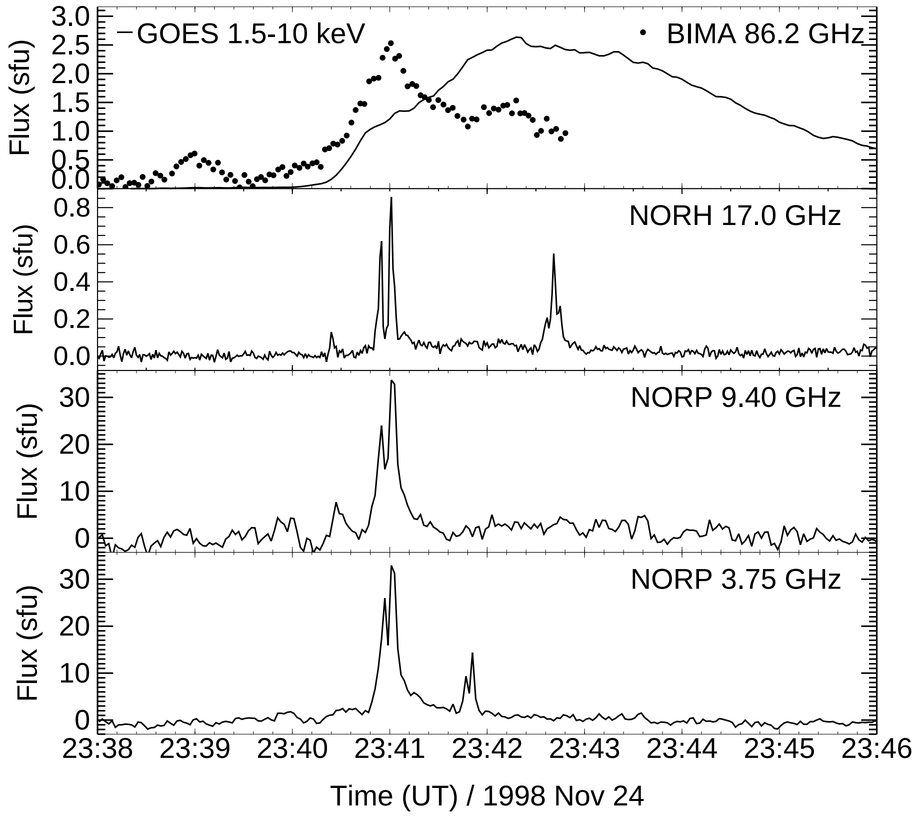

Figure 2. Radio and soft X–ray time profiles for the event of 1998 Nov. 24. The upper panel shows the BIMA flux at 86 GHz on the shortest baseline, which should represent the total flux of the event (dots), while the solid line is the GOES 1.5 – 10 keV channel time profile in a linear display. The second panel shows the NRH 17 GHz time profile derived from the correlation coefficient, and the bottom two panels show the 9.4 and 3.75 GHz fluxes as measured ny the Nobeyama polarimeters.

bipolar structure. Note that the absolute position of the 86 GHz source is not well determined due to the weather conditions and the position shown is based on matching the structure at the two frequencies. This is the first event in which a compact bipolar structure is seen at 86 GHz. There is no polarization information in the BIMA data (since a single linear polarization is detected), while the 17 GHz images show a polarization signal but not from the flare source: rather, we believe that it comes from a sunspot source to the west of the flare.

This is the first event we know of in which a compact bipole is seen at 86 GHz. The interest in such an outcome is that the morphology of these sources can be very revealing. Except in the largest flares, millimeter sources will be optically thin and the optical depth will largely determine the fluxes observed. Gyrosynchrotron emissivity (the mechanism by which nonthermal electrons emit at millimeter wavelengths) is a very strong function of magnetic field strength,

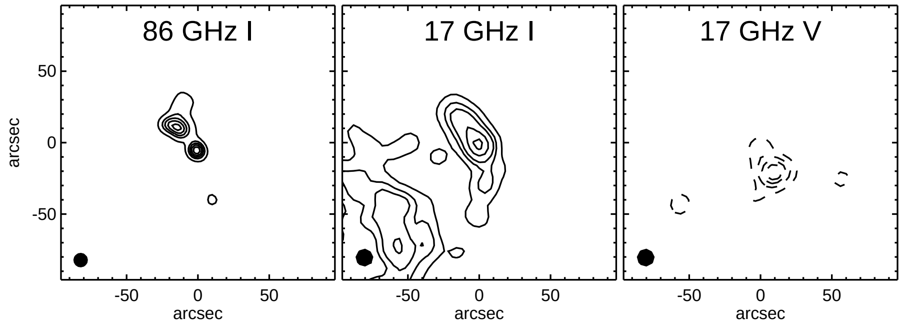

Figure 3. Images of the 1998 Nov. 24 event at 86 GHz from BIMA (one linear polarization, equivalent to total flux, left panel), NRH 17 GHz in total intensity (middle panel) and 17 GHz circularly–polarized flux (right panel). The images are at 23:41:20 UT. The beam sizes are $10''$ at 86 GHz and $12''$ at 17 GHz. Contours at 86 GHz are at levels of order 0.1 sfu per beam; at 17 GHz I, contours are at brightness temperatures of 20, 30, 40, 60, 80 and 100 $\times$ 10^3 K, and at 17 GHz V the contours are at brightness temperatures of 4, 8, 12, 16, 24, 32 and 40 $\times$ 10^3 K.

but electrons trapped in a loop will mirror back and forth between heights of equal magnetic field strength at the two ends of the loop and thus the maximum field strength they experience will be the same at both ends. In this case the main determinant of optical depth for trapped electrons will be the angle θ between the line of sight and the magnetic field, and this could be quite different at the two ends of the loop. Gyrosynchrotron calculations suggest that the emissivity depends on, e.g., $\sin^2\theta$ for an E^{-4} energy distribution (e.g., Dulk 1985). Thus when the millimeter emission is due to electrons trapped in a loop, we expect the two ends of the loop to be bright but not equally so; there should be enough dynamic range in BIMA observations to detect both footpoints. On the other hand, directly precipitating electrons can experience very different field strengths in the two feet, and since emissivity $\propto B^3$ for an E^{-4} energy distribution, the difference in flux between the two footpoints can be very large, perhaps more than the dynamic range which a snapshot BIMA observation can achieve.

Note that the EIT post–flare source in this event is very compact, more so than the radio source, and is confined to just one end of the radio source while the brightest radio emission actually arises at the other end during the flare peak (Fig. 3). This is consistent with a scenario in which most electron precipitation, and hence generation of heated chromospheric material, occurs at the weaker–field end of the loop while the radio emission is stronger at the stronger–field end of the loop.

3. Event of 1999 May 1

This event was a GOES class C3 flare occurring at N22W40 at 23:00 UT on 1999 May 1. Figure 4 shows the radio and soft X–ray time profiles of the event. This was a C3.0 flare occurring at N22W40 at 23:00 UT. The GOES profile for

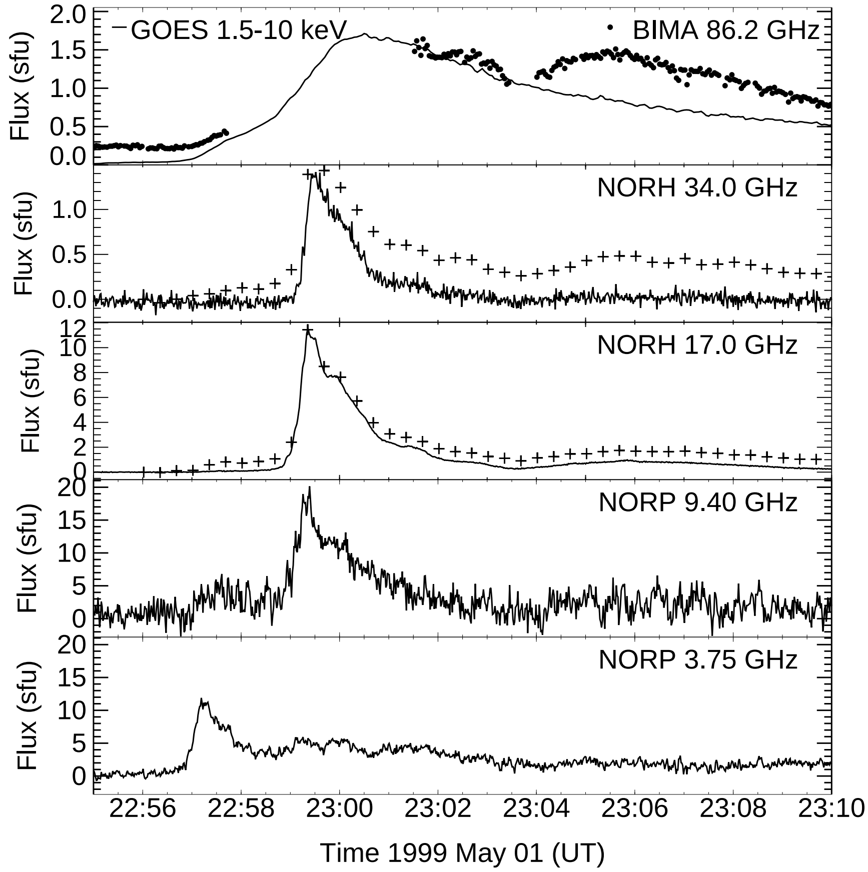

Figure 4. Radio and soft X–ray time profiles for the event of 1999 May 1 in the format of Fig. 1, with the addition of 34 GHz data from the Nobeyama radioheliograph. In the 17 and 34 GHz panels, the solid line is the 1 s correlation-plot data which samples only small spatial scales, while the plus symbols show total fluxes derived from images at specific times.

this event is very interesting. The initial rise is at 22:54 UT; the rise accelerates at 22:57 UT and then again at 22:59 UT before peaking at 23:00:30. Thus a number of energy releases seem to contribute to the event in soft X-rays.

The microwave profiles are equally interesting. A burst confined to low frequencies is seen at 22:57 UT corresponding to one jump in the GOES profile, and a second high–frequency burst is seen at 22:59 UT corresponding to the second jump in the GOES profile.

This event was clearly detected at 34 GHz by NRH with a time profile matching that at 17 GHz. Unfortunately BIMA missed the high–frequency peak due to a calibration scan. Prior to the calibration scan BIMA sees a small rise corresponding to the low–frequency microwave peak; however, the BIMA emission is not impulsive and looks more like a reflection of the GOES profile, i.e. is probably thermal free–free emission. When BIMA returns after the calibration scan, it first sees a decay similar to that seen in microwaves and soft

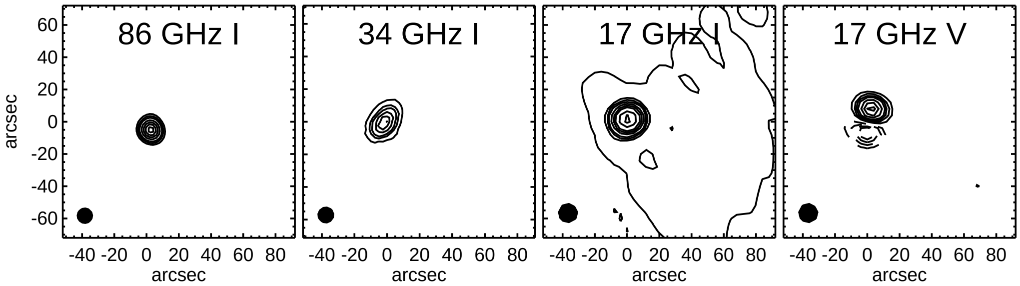

Figure 5. Images of the 1999 May 1 event at 23:02:00 UT. The format is similar to that of Fig. 3, with the exception that an additional panel shows the 34 GHz image from NRH. 86 GHz contours are at approximately 0.1 sfu per beam, 34 GHz contours are plotted at 20, 30, 40, 60 & 80 $\times$ 10^3 K, 17 GHz I contours are plotted at .02, .2, .3, .4, .6, .8, 1, 1.5 and 2 $\times$ 10^6 K and 17 GHz V contours are plotted at 4, 8, 12, 16, 24, 32 and 40 $\times$ 10^3 K.

X-rays, but then after 23:04 an increase in the 86 GHz emission is seen, which is matched at 17 and 34 GHz. There is no corresponding feature in the GOES profile, so we believe that the radio emission is not thermal emission from post-flare 10^7 K material: it could be very flat-spectrum nonthermal emission, or else flat-spectrum thermal emission from cooler material which does not contribute significantly to the GOES profile. The difference between the solid line and the symbols in the 34 GHz time profile is a rough indication of the size of the source, and this sugests that the source was larger during the later stages of the event than in the impulsive rise.

Images of the emission at 86, 34 and 17 GHz at 23:02:00 UT are shown in Fig. 5. The 17 GHz images show only weak polarization during the flare, but during this period the 17 GHz source is clearly bipolar, with a structure indicating that the two components are separated by less than a beam width. This suggests that the radio source is again a bipolar loop, as in the previous event, but of a size too small to be clearly resolved at the available resolution. The 34 GHz source is unresolved with a beam of order $10''$, and no polarization images are available at 34 GHz. The 17 and 34 GHz sources are coincident with the BIMA 86 GHz source for most of the time, with some post-flare brightening at 17 GHz in a source to the north-west. The 17 GHz images do show some emission corresponding to the low-frequency event at 22:57, but the spatial location is identical to that of the main flare source.

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References

Dulk, G. A. 1985, ARA&A, 23, 169

Kundu, M. R., White, S. M., Gopalswamy, N., & Lim, J. 1994, ApJS, 90, 599