MICROWAVE IMAGING OBSERVATION OF AN ELECTRON STREAM IN A SOLAR FLARE

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ABSTRACT

We report a Nobeyama Radioheliograph (NoRH) microwave observation of a propagating feature of non-thermal emission in a solar flare. The flare had a very extended source well resolved by NoRH. In the rising phase of the microwave burst, a non-thermal gyrosynchrotron source was observed by the high-rate (10 images per second) observations to propagate from one end of the loop to the other with a speed of 9×10^4 km s^{-1}. We interpret this non-thermal propagating source is emitted from streaming electrons.

RESULTS AND DISCUSSION

The flare in this report occurred on August 28, 1999 at S25 W11 as an M2.8 event for the GOES soft X-ray class (Yokoyama et al. 2002). The main microwave structure of the flare consists of a point source and an elongated one (Figure 1). From the spatial coalignment with the magnetograms obtained by SOHO/MDI, it is found that the point source is located near a sunspot. And also the opposite polarities at the two ends of the elongated source suggest that this is a magnetic loop. We can interpret the emission from the elongated source to be due to the non-thermal gyrosynchrotron mechanism based on the following diagnostics. Gyroresonance emission is ruled out because the emission comes from the site where the magnetic strength is not strong enough to emit 17 GHz microwave. The thermal free-free mechanism is also ruled out because the brightness temperature T_b, which was $T_b = 8.7 \times 10^6$ K at 00:56:42 UT at the peak, is too intense to be explained by such thermal emission (e.g. Dulk 1985). Therefore, the most probable emission mechanism is non-thermal gyrosynchrotron emission.

From the intensity ratio of the 34 GHz image to the 17 GHz, power-law index of the flux density α is determined, whose definition here is $F_\nu \propto \nu^\alpha$, where F_ν and ν are the flux density and the frequency, respectively. Note that to obtain this α-map, the 17 GHz image is convolved with the 34 GHz beam and vice versa since NoRH has different size of the beams at different observation frequencies. Most of the emission from the elongated source has negative α, that is optically thin. Therefore we can obtain the power-law index δ of the emitting electrons' distribution function. Based on Dulk (1985)'s approximation formula, it is given as $\delta \approx -1.1(\alpha - 1.2)$. From this interpretation, the electron power-law index is $\approx$ 4–5 at the two ends of the elongated source and is ≈ 3 between them.

We find several propagation features of the non-thermal sources from the south-east end to the north-west end of the elongated loop (Figure 1). They are clearly seen in a movie of the 0.1-s cadence images from around 00:56:10 UT near the peak of the event. The fastest propagation among them is shown in Figure 2. Propagating profiles from the left bottom of the plot (corresponding to the south-east end) to the top (the

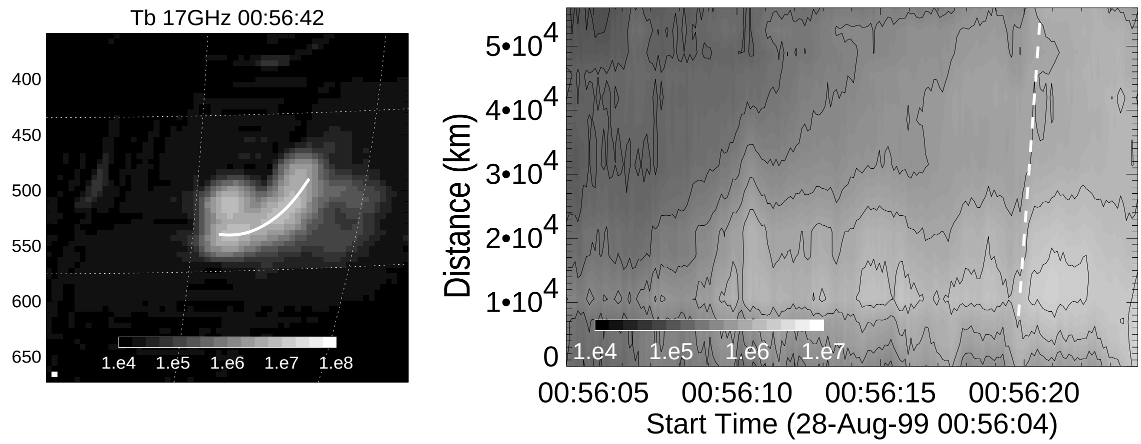

Figure 1: Time variation of the 17 GHz intensity distribution along the microwave 'loop' indicated by the solid white line in the left panel. The left lower corner of the loop correspond to the 0 km in the vertical axis of the right panel. Note the propagation around 00:56:20 UT whose speed is $\approx 9 \times 10^4$ km s^{-1} (indicated by thick white dashed line).

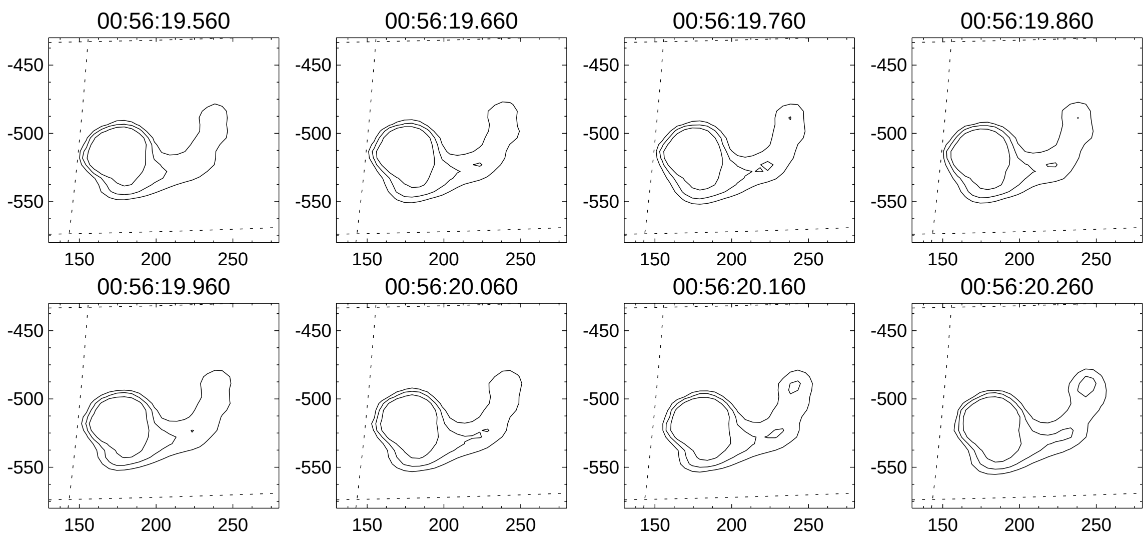

Figure 2: NoRH images of the microwave emission at 17 GHz at selected times. Solid contours indicate the level of $T_{\rm b} = 5.6,\ 10.,\ 18. \times 10^5$ K at 17 GHz. Note that the first signature of the propagation is seen at 00:56:19.660 UT and it reaches the other loop end at 00:56:20.160. The distance between these sources are 4.5×10^4 km. Thus, the apparent velocity is $\approx 9 \times 10^4$ km s^{-1}.

north-west end) can be seen. The propagation duration is 0.5 second from 00:56:19.66 to 00:56:20.16 UT and the distance is 4.5×10^4 km. Thus, this rough estimation gives a speed of 9.0 $\times 10^4$ km s^{-1} that is 30 % of the light speed.

We interpret this non-thermal propagating source is emitted from streaming electrons (White, Janardhan, & Kundu 2000). An apparent velocity of 9×10^4 km s^{-1} corresponds to the energy of $\approx$ 23 keV. This apparently seems to be much less than the energy necessary for emitting the microwaves (17 GHz). The actual energy of electrons which may mostly contribute to the 17 GHz emission in this event can be estimated as follows. By using the potential magnetic field obtained by extending the magnetogram data on the photosphere by SOHO/MDI, we obtain the distribution of the magnetic field strength along the loop, which is approximately 200 Gauss in the middle area of the loop. As noted above, the power-law index of the electrons are derived to be $\delta = 4$. According to the estimation by Bastian (1999), the energy of the electrons which mainly contribute to the gyrosynchrotron emission at 17 GHz is 1.3 MeV when the background magnetic field strength is 200 Gauss and the power-law index of electrons is $\delta = 4$. Thus, the actual velocity of the electrons is close to

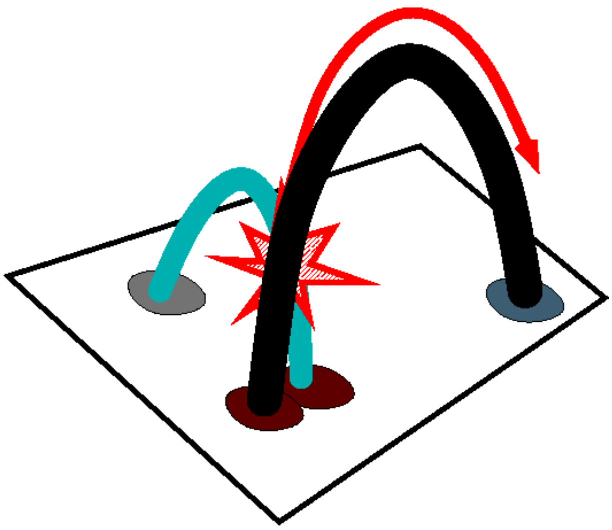

Figure 3: Schematic picture of our model. Thick lines indicate the magnetic loops in the corona. The arrow indicates the propagation of electrons which were thought to be the source of the propagating non-thermal microwave source in this paper. Two systems of magnetic flux reconnect with each other and give the magnetic energy partially to the high-energy electrons.

the light speed. The observed apparent velocity 9×10^4 km s^{-1} ($\approx$ 23 keV) is much less than the light speed. If we suppose that the bulk of energetic electrons was injected into the magnetic loop at some large angle to the field lines, then one can explain the low apparent velocity by the fact that the electrons were rotating around the magnetic field lines and the effective path was much longer than the apparent length of the loops. In this case, the pitch angle of the electrons is $\alpha_{\rm pitch} \approx \arccos{(v/c)} \approx 70$ degree where v is the apparent velocity $v \approx 9 \times 10^4$ km s^{-1} and c is the speed of light. This may suggest that there is a possibility that the high energy electrons have large (> 70 degree) pitch angles when they are injected. We cannot specify which acceleration mechanism is consistent with this observational limitation at this moment. But the acceleration by a simple field-aligned electric field seems to be ruled out, at least, for this particular observation. Note that the idea of a perpendicular injection is also used for the explanation of the spectral evolution (Lee & Gary 2000) and the localization near the loop top (Melnikov et al. 2002) in the microwave observations.

As Figure 2 shows, the acceleration site of the high energy electrons is located near the south-east end of the loop where the propagation of the non-thermal signal starts from. The primary energy release site, therefore, is around this area. We consider that this is caused by the moving parasitic polarity located just east of the compact microwave source near the south-east end of the loop where a relatively strong magnetic spot is located. From August 27 to the next day, a negative (opposite to the spot) parasitic polarity emerges just in the east of the spot and then moves to the west toward the spot with velocity of 0.2 km s^{-1}. This motion may cause the magnetic reconnection (Figure 3) with the pre-existing large scale loops connecting the sunspot positive polarity and the negative polarity near the northwest end of the elongated source. This situation is similar to the configuration suggested by Hanaoka (1999) and Nishio et al. (1997).

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