Behavior of Accelerated Electrons in a Small Impulsive Solar Flare on 1992 August 12

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Abstract

A GOES C1.0-class impulsive flare was observed by the new Nobeyama Radioheliograph on 1992 August 12 with 1 s temporal and 10" spatial resolutions at 17 GHz. The radio flare consisted of an impulsive phase of ~ 20 s and a decay phase of ~ 90 s. Radio images showed double sources in the impulsive phase, whereas in the decay phase a single elongated source appeared which connected the double sources. Soft X-ray images with Yohkoh/SXT show that the radio double sources correspond to foot points of newly appearing coronal loops and the single source was located at the top of one of the loops. The radio emission for both phases can be explained by gyrosynchrotron radiation from accelerated electrons. These loops began to brighten at their intersecting point ~ 1 min before the radio flare. All of these facts suggest that the reconnection of magnetic fields heated up the coronal loops and produced accelerated electrons, which ran through the loops, precipitated onto the foot points, and caused the radio flare. Less than 1% of the electrons were mirrored at the foot points and trapped at the top of the loop. The lack of radio emission in the loop top area during the impulsive phase implies that the accelerated electrons were highly beamed.

Key words: Interferometers — Particle acceleration — Sun: flares — Sun: radio radiation — Sun: X-rays

1. Introduction

Solar flares observed in the microwave range often show impulsive light curves. The emission is thought to be gyrosynchrotron radiation from accelerated nonthermal electrons interacting with magnetic fields. The behavior of accelerated electrons in flares, however, has not yet been well-known, e.g., where they are accelerated, what distribution they have in pitch angle, and how many of them are precipitated into the chromosphere and reflected into the corona at the foot points of coronal loops. Consequently, the mechanisms of acceleration in flares have not yet been well solved.

Imaging observations of radio impulsive flares, with appropriate temporal and spatial resolutions, can provide the most direct information for understanding the behavior of electrons, because radio emission originates from live accelerated electrons instead of those that are braked or thermalized, such as in the case of hard X-rays or Hα.

In order to reach this goal, we constructed a new instrument, the Nobeyama Radioheliograph. It is operated at 17 GHz and has a high temporal resolution of 50 ms and a spatial resolution of ~10" with high image qualities (Nakajima et al. 1994). The Radioheliograph started daily observations in 1992 July. From the beginning of routine observations it has observed various flares and other interesting phenomena, part of which were summarized by Enome et al. (1993).

In this paper we present observational results of a small impulsive flare using the Radioheliograph together with soft X-ray observations with the satellite Yohkoh (Ogawara et al. 1991) as well as observations with the Solar Flare Telescope at Mitaka (Ichimoto et al. 1991).

2. Observations and Results

An impulsive flare occurred at 0436 UT on 1992 August 12 in the active region NOAA 7248. The heliographic coordinate of the region was 53°W 17°S. The GOES soft
Fig. 1. Radio images (a) before, (b) in the impulsive phase, and (c) in the decay phase of the flare on 1992 August 12. The upper panels are images for R+L and the lower ones are those for R−L. The size of the images are 59″ × 79″. The pixel size of the images is 46′′ × 46′′. The contours in each frame are of 25, 50, 75% of each peak. Because there were no significant polarized sources before the flare, we omitted contours in panel (a−2). The peak brightness temperatures for the three R+L maps are 37, 351, and 147 × 10^6 K for (a), (b), and (c), respectively.

X-ray class of the flare was C1.0 and the radio flux at 17 GHz measured with the Radioheliograph was 5.4 sfl. Radio images of the flare are shown in figure 1. The Soft X-ray Telescope (hereafter SXT; Tsuneta et al. 1991) on Yohkoh also observed this region and took images of the sun (figure 2). A magnetogram taken with the Solar Flare Telescope is shown in figure 2k.

The light curve of radio emission averaged over a 59″ × 79″ area is shown in figure 3. The curve shows that the flare consisted of an impulsive phase of ~20 s duration and a decay phase of ~90 s. The radio spectra for both phases are shown in figure 4; the data were taken with the radio polarimeters at Toyokawa at 2, 3.75, and 9.4 GHz, and combined with the data at 17 GHz with the Radioheliograph.

The radio images show double sources separated by 35″ from each other in the impulsive phase, whereas a single elongated source appeared in the decay phase. The light curves at these three sources (named Radio-1, Radio-2, and Radio-3) are shown in figure 3. The degrees of polarization were ~10% for Radio-1 and -2, and ~25% for Radio-3.

Temperatures and emission measures of the gas can be derived from the intensity ratios of the SXT images taken through 0.1 and 12 μm thick aluminum filters (Harra et al. 1992). Because the SXT images changed significantly from one to another, and two kinds of images were taken alternately, we averaged the images of figure 2a and 2c for deriving ratio to 2b for the values before the radio flare, and averaged the images of figure 2d and 2f for ratio to 2e for the values after the radio flare. The derived temperatures are 5–10 × 10^6 K at the positions corresponding to the three radio sources before the radio flare and show only a slight increase (at most 20%) after it. The emission measures were 20–40 × 10^4 cm^−3 per pixel before the radio flare, but increased by 2–4 times after it. The electron density n_e can be derived as ~10^{10} cm^−3 from the emission measures, assuming that the depth of the emitting region is L ~ 10^9 cm, which corresponds to the typical width of the Loops.

3. Discussion

3.1. Magnetic Loop Structures

The SXT images reveal three coronal loops in area. A loop called Loop-1 had already been seen before the radio flare. Loop-2 appeared ~1 min before the onset of the radio flare, as shown by arrow "A" in figures 2b and c, and strongly brightened together with the other new loop, Loop-3, after the radio flare. The southern foot of Loop-2 was located at the same position of the northern foot of Loop-1, and the southern feet of Loop-1 and -3 were located at a common position. The northern end of Loop-3 seems to be connected with the top of Loop-2, as shown by arrow "B" in figure 2c. Superposed maps of the radio and the SXT images show that Radio-3 corresponds to Loop-3 and that Radio-2 corresponds to the southern foot of Loop-3. Radio-1 corresponds to Loop-2 and the northern end of Loop-3.

Because of a lack of magnetograms during the flare, and a possible change in the magnetic fields due to the activity in the region, it is difficult to know the exact photospheric magnetic polarities at the foot points of the SXT loops. Actually, a magnetogram obtained at Kitt Peak at 1526 UT shows different polarities from the Mitaka magnetogram at some of the foot points of the loops. We therefore speculate a magnetic connectivity of the loops from the SXT images and the observed polarization of Radio-1 and -2, as illustrated in figure 2t. We could interpret the reason why Radio-1 shows the R polarization as being that the dominant emission came from the N polarity foot of Loop-2.

3.2. Mechanisms of Radio Emission in the Flare

The radio spectra of the flare have peaks at ~6 GHz for both the impulsive and the decay phase. This type of
spectra cannot be produced by free-free emission from thermal electrons (Dulk 1985). Because of the small degrees of radio polarization (≤ 25%) and much lower brightness temperatures relative to the gas temperature, gyroresonance emission from thermal electrons is also ruled out for the emission mechanisms in this flare.

It is clear that the radio emission in the impulsive phase was of the gyrosynchrotron type from high-energy electrons accelerated with the flare, because of the facts discussed above as well as the facts that the sources in this phase were located on the foot points of the SXT Loop-3 and had a short duration. Although the dominant emission mechanism in the decay phase for the observed frequency range was also nonthermal gyrosynchrotron as discussed above, it could be possible that part of the emission at 17 GHz was of thermal free-free emission. A comparison between the radio and soft X-ray light-curves at the top of Loop-3 shows that the radio emission more rapidly increased and decreased than that of soft X-rays, as shown in figure 5. This fact suggests that the role of the thermal free-free emission at 17 GHz should also be small in the decay phase.

We estimated the physical parameters using equations derived by Dulk (1985). The electron energy spectral index δ was estimated to be 5 and 3 for the impulsive and decay phases, respectively, based on the observed spectral index α in the optically thin part. Using the derived δ and observed degree of polarization, r_p ~ 24%, we evaluated the intensities of the magnetic fields B to be 400±130 Gauss for the decay phase under the assumption of the angle between the fields and the line of sight θ ~ 70–90°, taking into account the heliographic coordinate of the region and the orientation of Loop-3. This value is similar to that of the magnetic fields in the magnetogram. We obtained the peak flux frequencies ν_p to be 6.5 ± 0.5 GHz and 5.5±0.8 GHz for the impulsive and the decay phases, respectively. Using the derived B and ν_p, we estimated the number densities of accelerated electrons N (E > 10 keV) to be (1.5 ± 0.2) × 10^6 cm⁻³ for the decay phase, assuming that L ~ 1.2 × 10^9 cm, which corresponds to the width of Loop-3, and θ = 70–90°. For the impulsive phase, N was 10^7–10^8 cm⁻³, assuming that B ≈ 400–800 Gauss and θ = 50°.
3.3. Behavior of Accelerated Electrons in the Flare

The SXT image in figure 2c suggests that position “A” is the intersecting point of Loop-2 and -3. We interpret that the reconnection of magnetic fields occurred at “A.” After reconnection, heating of the gas in these loops started first; next, electrons were accelerated at position “A.” The released high-energy electrons ran through Loop-2 and -3, precipitated onto the foot points, and caused the radio double sources in the impulsive phase of the flare. The supply of electrons ceased within the first 20 s at the end of impulsive phase. Part of precipitated electrons were mirrored at the foot points, and those with large pitch angles were trapped in the loop top area of Loop-2 and -3. Although the mirrored electrons in Loop-2 rapidly decayed because of high density plasma, those in Loop-3 were accumulated and survived for \( \sim 50 \) s, which corresponds with the lifetime that 100 keV electrons would have in an ambient plasma of \( 10^{10} \text{ cm}^{-3} \), derived from SXT data. The fraction of reflected electrons was, therefore, estimated to be less than 1%, taking into account the lifetimes of the electrons in the both phases and the derived \( N \).

Radio-3 did not brighten before the peak intensity in the impulsive phase, as shown in figure 3, although the number of electrons in this phase was more than 100 times larger than that in the decay phase. This fact implies that the accelerated electrons running through the top of SXT Loop-3 in the impulsive phase had much smaller interaction with the magnetic fields than that in the decay phase. If we assume no significant change in the strengths and structures of the magnetic fields between these phases, a probable explanation for this fact is that the accelerated electrons supplied in the impulsive phase were highly beamed with extremely small pitch angles.

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