A BROADBAND MICROWAVE BURST PRODUCED BY ELECTRON BEAMS

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ABSTRACT

The theoretical and experimental study of fast electron beams attracts much attention in astrophysics and the laboratory. In the case of solar flares, the problem of reliable beam detection and diagnostics is of exceptional importance. This paper explores the fact that electron beams moving obliquely to the magnetic field or along the field with some angular scatter around the beam’s propagation direction can generate microwave continuum bursts through the gyro-synchrotron mechanism. The characteristics of the microwave bursts produced by beams differ from those in the case of isotropic or loss-cone distributions, which suggests a new quantitative diagnostic for beams in the solar corona. To demonstrate the potential of this tool, we analyze a radio burst that occurred during an impulsive class IB/M6.7 flare on 2001 March 10 (NOAA AR 9368; N27°, W42°). Based on detailed analysis of the spectral, temporal, and spatial relationships, we obtain firm evidence that the microwave continuum burst was produced by electron beams. We develop and apply a new forward-fitting algorithm based on the exact gyro-synchrotron formulae and employing both total-power and polarization measurements to solve the inverse problem of the beam diagnostics. The burst is found to have been generated by an oblique beam in a region of reasonably strong magnetic field (~200–300 G) and observed at a quasi-transverse viewing angle. We find that the lifetime of the emitting electrons in the radio source was relatively short, τ1 ≈ 0.5 s, consistent with a single reflection of the electrons from a magnetic mirror at the footpoint with the stronger magnetic field. We discuss the implications of these findings for electron acceleration in flares and beam diagnostics.

Subject headings: acceleration of particles — Sun: flares — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Electron beams are believed to represent an important elementary ingredient of solar activity (Aschwanden 2002 and references therein). They ionize and excite hydrogen atoms in the chromosphere, giving rise to optical Hα flares. They are capable of producing nonthermal hard X-ray (HXR) and gamma-ray radiation by means of the bremsstrahlung mechanism, as well as being capable of driving chromospheric evaporation. Then, they can drive various kinetic instabilities in the corona, giving rise to a variety of coherent radio emission types widely observed throughout the radio band (Aschwanden 2005).

Nevertheless, there is an apparent lack of observational tools at present to provide quantitative diagnostics of the electron beams in the solar atmosphere. Currently, Hα, HXR, and gamma emissions, as well as type III bursts in the radio range, are considered to represent the signatures of electron beams. However, these processes do not offer any reliable, straightforward diagnostics of the angular distributions of the beams. Even though valuable information on the electron-beam properties might in principle be derived from the linear polarization of the Hα and Hβ lines in chromospheric flares (Henoux et al. 2003), the measurement of linear polarization in these spectral lines is extremely difficult, so the corresponding beam diagnostic has not been established yet (Bianda et al. 2005). In the case of HXR and gamma emissions, no method has been proposed so far to extract the angular distribution of fast electrons from the data. Moreover, many HXR bursts originate from coronal rather than chromospheric sources (Veronig & Brown 2004), although even in the case of a chromospheric source, the HXR emission can originate from a precipitating fraction of approximately isotropic electron distributions rather than from beams. Finally, any diagnostics based on type III bursts will be difficult, because for a coherent process the dependence of the output radiation on the electron-beam properties is highly nonlinear and difficult to disentangle (Aschwanden 2002). On the other hand, a beam can be invisible in terms of type III emission if it propagates in a dense plasma, where a high collisional damping rate will quench the beam instability and prevent the generation of coherent emission. On top of this, the observed fast drifting of radio fine structures is not necessarily related to beam propagation: it can be provided by the dynamics of MHD and reconnection processes as well (Altyntsev et al. 2007), while lower values of the drift rate can be ascribed to emission originating at thermal conduction fronts (Farník & Karlický 2007).

We can conclude that the tools currently available are insufficient for reliable detection and detailed diagnostics of the beams in the solar corona.

Curiously, one of the most promising methods of study, namely, analysis of beam-produced microwave gyro-synchrotron radiation, remains entirely unexplored, although synchrotron radiation by nonthermal electrons was long ago recognized as the main mechanism producing the microwave emission in solar flares (Ramaty 1969; Ramaty & Petrosian 1972; Benka & Holman 1992; Bastian et al. 1998; Nindos et al. 2000; Kundu et al. 2001; Trottet et al. 2002; Bastian 2006; Gary 2006; Nindos 2006). Exact expressions for the gyro-synchrotron emission and absorption coefficients (Eidman 1958, 1959; Ramaty 1969; Ramaty et al. 1994) are cumbersome and difficult to use directly. Thus, significant efforts have been made to find simple analytical approximations for both the synchrotron emission in the ultrarelativistic case (Ginzburg 1951; Korchak & Terletsky 1952; Getmantsev 1952; Ginzburg 1953; Korchak 1957; Ginzburg & Syrovatskii 1964) and the gyro-synchrotron emission generated by nonrelativistic...
and moderately relativistic electrons (Dulk & Marsh 1982; Dulk 1985; Zhou et al. 1999). In addition, simplified, numerically fast computational schemes have been developed (Petrosian 1981; Klein 1987). All these studies, however, have assumed electron distributions that are isotropic or, in some cases, only weakly anisotropic. These approximations are evidently insufficient to describe and analyze beam-produced gyrosynchrotron emission, for which the pitch-angle anisotropy is expected to be strong.

Recently, Fleishman & Melnikov (2003) discovered a significant effect of the pitch-angle anisotropy on the gyrosynchrotron spectrum and polarization. So far (for a review, see Fleishman 2006), analysis of microwave continuum bursts has provided ample evidence of a loss-cone particle distribution formed as the result of trapping of the accelerated electrons in coronal magnetic loops (Melnikov et al. 2002; Melnikov 2006; Fleishman et al. 2003, 2008). By contrast, here we present a different class of events in which there is a beamlke anisotropy in the particle distribution.

In the case of a beamlke angular distribution of fast electrons, in particular, the high-frequency spectral index will depend noticeably on the anisotropy and the viewing angle, in addition to the standard dependence on the energy distribution. The degree of polarization can differ strongly from that in the isotropic case. Remarkably, the sense of polarization can correspond to the ordinary wave mode (O-mode) in the optically thin range of the spectrum, in contrast to X-mode polarization in the isotropic case (Fleishman & Melnikov 2003).

Thus, beamlke anisotropy, when present, must be properly taken into account for correct modeling of solar microwave continuum bursts, which is especially important in interpreting the polarization spectra. The goal of our study is to identify an example of a microwave burst in which the presence of electron beams is likely and then evaluate the properties of the pitch-angle distribution and, perhaps, other relevant parameters of the source from a forward fitting of the gyrosynchrotron formulae to the observed radio data.

The criteria to identify a candidate beam-produced microwave burst are the presence of short (on the order of seconds) broadband pulses, type III--like drifting bursts at lower frequencies, or both. Among many burst candidates, we eventually selected the event of 2001 March 10. This selection is based on a fortuitous combination of radio observations of this burst by different observatories, as well as the availability of other important context observations for this event.

Below we describe the key observational characteristics of the event, suggest a semiquantitative interpretation of the data, and then describe a specially developed nonlinear $\chi^2$ minimization fit and apply it simultaneously to the total-power and polarization spectra. Eventually, the fitting yields the parameters of the angular distribution of the radiating electrons, the viewing angle of the emission, and the characteristic lifetime of the electrons at the radio source.

2. INSTRUMENTATION

The event was observed by a number of radio instruments:

The Nobeyama Radio Polariometer (NoRP; Torii et al. 1979; Nakajima et al. 1985) measures total and circularly polarized intensities (Stokes parameters $I$ and $V$) at 1, 2, 3.75, 9, 4, 17, 35, and 80 (Stokes $I$ only) GHz with time resolution as high as 0.1 s. We applied corrections provided by the Nobeyama team for the polarization data at 1 and 2 GHz and the intensity data at 80 GHz, available at the Nobeyama Radio Observatory Internet archives.

The Chinese Solar Broadband Radio Spectrometers (SBRSs; Fu et al. 2004) measure total and polarized flux at frequencies of 5.2--7.6 GHz with 20 MHz spectral and 5 ms temporal resolution (NAOC, Huairou station), as well as the total flux at frequencies 4.5--7.5 GHz with 10 MHz spectral and 5 ms temporal resolution (Purple Mountain Observatory).

The Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994) obtains images of the Sun at 17 GHz (Stokes $I$ and $V$) and 34 GHz (Stokes $I$) with 0.1 s temporal resolution. At the time of the burst, the NoRH angular resolution was 17" at 17 GHz and 10" at 34 GHz.

Fortuitously, data from another large imaging instrument, the Siberian Solar Radio Telescope (SSRT; Smolkov et al. 1986; Grechnev et al. 2003), are available for this burst. SSRT produces one-dimensional brightness distributions at 5.7 GHz with 14 ms temporal resolution. During observation of this burst, the knife-edge beam of the north-south linear array (SSRT/NS) was directed 43.53" from the central solar meridian (angular resolution of 24").

The east-west array (SSRT/EW) knife-edge beam was directed $-23.61$" from the central solar meridian, with an angular width of 16.5".

HXR observations made by the Yohkoh satellite’s Hard X-Ray Telescope (HXT) in four energy bands (L band, 14--23 keV; M1 band, 23--33 keV; M2 band, 33-53 keV; and H band, 53--93 keV) and Wide Band Spectrometer (WBS; Yoshimori et al. 1992) in the high- (80--600 keV) and low-energy bands (20--80 keV) are available.

In addition, context data from the Solar and Heliospheric Observatory Michelson Doppler Imager (MDI) for the magnetic field and EUV Imaging Telescope (EIT) are available for this flare.

3. OBSERVATIONS

This impulsive flare (2001 March 10, 1B/M6.7) occurred in NOAA Active Region 9368 (N27°, W42°). NoRP recorded an intense microwave burst in all frequency channels (Fig. 1, left). The light curves throughout all these frequencies except 1 GHz display a very short (about 3 s duration) broadband peak at 04:03:39.6 UT. The pulse magnitudes were exceptionally strong in the range 9.4--35 GHz (>1000 solar flux units).

Analysis of this flare at different wavelengths, namely, Hα, hard and soft X-rays, and radio waves, was published in a number of papers. Liu et al. (2001), Ding et al. (2003), and Ding (2003) classified this as a white-light flare. From the good time correlation of Hα and Ca ii λ8542 brightenings with the peak of the microwave radio flux, they concluded that the response in optical emission was due to chromospheric heating by an electron beam. Uddin (2004) and Chandra et al. (2006) studied the evolution of the flare active region and associated this flare with a small positive-polarity region emerging near the following negative sunspot. They distinguished two bright Hα kernels connected by a dense plasma loop, with a distance of about 10⁴ km between the footpoints.

3.1. Temporal Characteristics

The entire burst duration is rather short (~40 s) at frequencies above 3.75 GHz. The time profiles are remarkably similar to one another, and the duration of the most prominent peak is the same throughout the entire spectral range. The light curves at 9.4--80 GHz peak at the same time, while that at 3.75 GHz is delayed by a fraction of second and that at 2 GHz is delayed even longer (by half a second). It is interesting that the decay time becomes slightly larger at low frequencies.

The NoRP time profiles of the circularly polarized radiation (Stokes $V$) are shown in the right panels of Figure 1. Except at
35 GHz, the profiles of the polarized fluxes differ essentially from the total-power profiles. The degree of polarization varies from +10% at 1 GHz down to −10% at 35 GHz. The main peak is clearly distinguishable at 3.75, 9.4, and 35 GHz. Note that across the NoRP spectrum, right-circular polarization gives way to left-circular somewhere between 3.75 and 9.4 GHz. Analysis of the SBRS data in the 5.2–7.6 GHz range shows that this polarization reversal occurs around 6.5 GHz.

In the dynamic spectrum (Fig. 2, top), the NoRP data are complemented by the SBRS profiles at 5.4 and 7.4 GHz to fill the large gap between the NoRP receiving frequencies of 3.75 and 9.4 GHz. The shape of the microwave spectrum does not change much during the burst, as visualized by the similarity of the contours of equal intensity shown in the dynamic spectrum. The time profiles in Figure 1 show a number of pulses besides the main peak. These are clearly seen in the time derivative of the dynamic spectrum (Fig. 2, bottom), which shows wideband fine structures during the entire burst. Bright stripes correspond to an increase in emission, while dark ones show emission decrease. The width (duration) of the shortest stripes is comparable to the NoRP temporal

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**Fig. 1.**—Microwave fluxes recorded by the NoRP polarimeters. Left, total intensity (R+L); right, polarized intensity (R−L). Magnitudes are in solar flux units (sfu).

**Fig. 2.**—Top: Dynamic spectrum of the 2001 March 10 flare burst. The NoRP measurements are complemented by SBRS measurements at 5.4 and 7.4 GHz. Contours are at 2000 × (0.1, 0.3, 0.5, 0.8) sfu. Bottom: The derivatives of the time profiles.
resolution (0.1 s), and their bandwidth covers the entire spectral range from 1 to 80 GHz in some cases. The stripes are not noise or interference, since they are wider than several frequency channels and include data from different observatories. Note that most of the broadband pulses display no frequency drift, although any drift value within \( \pm 800 \text{ GHz s}^{-1} \) is measurable with the given time resolution (0.1 s) and spectral bandwidth (80 GHz) of the pulses. The duration of the decay phases (dark stripes after bright ones) does not depend on frequency.

At millisecond timescales, there are pulses with reverse and normal frequency drifts observed in the dynamic spectrum in the interval from 04:03:37 to 04:03:56 UT, some of which are shown in Figure 3. The total bandwidth of these fine structures does not exceed 0.5 GHz, and their lifetime is about 50 ms. The corresponding drift rates are within 10–15 GHz s\(^{-1}\) for this event. The characteristic frequency of the fine structures rises from 4.5 to 7 GHz during this interval.

The time profiles of the hard X-ray emission are remarkably similar to the microwave profiles (Fig. 4). The same profiles were observed with the Yohkoh WBS in the high-energy band (80–600 keV). Note that the HXR emission is delayed relative to the radio emission. The overall L-band signal is delayed relative to various radio frequencies by about 1–2 s, although the delay between the impulsive peaks occurring at about 04:03:40 UT is shorter than 1 s. At higher energies the delays are shorter, being a fraction of second. In particular, the cross-correlation between the H channel and the 35 GHz light curve yields a delay of 0.5 s with a correlation coefficient of 0.8.

3.2. Spatial Characteristics

The flare’s spatial structure in H\(\alpha\) emission was studied by Uddin et al. (2004) and Chandra et al. (2006). Before the flare, emerging flux of positive polarity penetrated into the negative-polarity region and triggered the flare. From the spatial correlation between sources in different wave bands, it was concluded that the flare had three-legged structure; that is, it may be considered to have had one of the typical loop configurations as determined earlier by Hanaoka (1996). The H\(\alpha\) flare began (around 04:01 UT) as two bright kernels (K1 and K2), which rapidly transformed during the flare peak into a bright region expanding in the southwest direction. A short loop connecting magnetic regions of opposite polarity is seen in 195 Å emission (Fig. 5); its length is about 10\(^4\) km. One more source (the so-called remote source, “RS”) appeared after 04:03:51 UT at 17 GHz. The RS was located 150° southwest of the main flare site (Fig. 5) and had right-circular polarization; the presence of the RS is confirmed by a secondary peak at 280° in the 5.7 GHz SSRT/NS scan at 04:04:21 UT (Fig. 6, middle), which is unpolarized, however, at this relatively low frequency.

The footpoints of the loop are seen in the 17 GHz polarization images during the late decay phase of the burst (Fig. 7, right). The maps shown in Figure 7 are the result of averaging the emission

![Fig. 3.—Drifting fine structures recorded slightly before the main flare peak with the Purple Mountain Observatory spectrometer.](image1)

![Fig. 4.—Radio vs. Yohkoh HXT light curves. Energy ranges are L (14–23 keV), M1 (23–33 keV), M2 (33–53 keV), and H (53–93 keV). The HXR light curves (dotted lines) are normalized so as to match the peak value of the corresponding radio light curves (solid lines). The HXT light curves are available at http://gedas22.stelab.nagoya-u.ac.jp/HXT/catalogue/image...html/cid...html/cid25110.html.](image2)
The microwave light curves. The peak time.

3.3. Description of the Spectrum

The microwave spectra are shown in Figure 8 (symbols) at three moments corresponding to the main and neighboring peaks. These spectra are similar to each other. At low frequencies, the spectra increase with index \( \gamma \approx 1.9 \). The spectral peak is at about 17 GHz. At high frequencies, the spectrum decreases rather quickly, with a high-frequency spectral index \( \gamma \approx -2.1 \).

The hard X-ray spectrum \( I(E) \) was studied by Chandra et al. (2006) using the Yohkoh HXT data. For the peak time they obtained \( I(E) = F_0 E^{-\gamma} = 2.02 \times 10^{55} E^{-2.4} \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1} \). Assuming an electron spectrum of the form \( F_\delta(E) = AE^{-\delta} \) electrons per second, we obtain the parameters of the electron flux under the thick-target assumption as follows, making the necessary corrections to the equation given by Brown (1971):

\[
A = 5.2 \times 10^{33} (\gamma - 1)^2 B(\gamma - 0.5, 1.5)F_0 = 5.1 \times 10^{39} \quad (1)
\]

and

\[
\delta = \gamma + 1 = 3.4, \text{ where } E \text{ is expressed in keV.}
\]

3.4. Summary of Observations

Here we summarize the main observational characteristics of the event that are important for further analysis:

1. The microwave emission in the 2001 March 10 event consists of many short broadband pulses.
2. Type III–like features are observed around 5 GHz.
3. The microwave emission is O-mode polarized at 17 GHz.
4. The polarization at 5.7 GHz displays high variability and corresponds to the X-mode at the peak time.
5. The HXR light curves are remarkably similar to the microwave light curves.
6. HXR emission is delayed by a fraction of second compared with the microwave emission.

4. MODEL

4.1. General Trends and Model Dependences

Our goal in the analysis of the microwave emission is to derive important source parameters from a forward fitting of the observed radio spectra with the gyrosynchrotron formulae. However, as is widely known (e.g., Bastian et al. 2007), the gyrosynchrotron emission depends on too many physical effects and parameters over more than a minute. The averaging was done because the brightness temperature of the right-circular emission was rather weak. In the main phase of the burst, the bulk of the microwave emission is generated in source K2, with positive magnetic field polarity, and it is left-circularly polarized. This means that the microwave source K2 is polarized in the ordinary wave mode. The magnetic field near the footpoints can be estimated from the MDI magnetogram as \(-170 \text{ G} \) (K1) and \(340 \text{ G} \) (K2).

The spatial behavior of the Yohkoh HXT emission was studied by Chandra et al. (2006) in detail. In all energy bands, only a single source is observed. The estimated size of the HXR source is \(7.0'' \times 3.8'', 6.7'' \times 3.3'', 6.5'' \times 3.3'', \) and \(6.2'' \times 3.2''\) in the L, M1, M2, and H energy bands, respectively. According to Figure 6 of Chandra et al. (2006), the HXR source is located near source K1. Note that a situation in which the hard X-ray and the microwave brightness peaks are located on the opposite ends of a single loop is typical of an asymmetric magnetic loop.

The one-dimensional SSRT images are shown in Figure 6. The vertical lines correspond to the integration paths crossing the centers of the two-dimensional brightness distribution at 17 GHz; these integration paths are shown by dash-dotted lines for both east-west and north-south linear arrays in Figure 5. The position of the microwave source did not change in the north-south scans, while it shifts slightly to the west in the east-west scans at the burst peak. The sources K1 and K2 are not resolved in the SSRT scans. The size of the 5.7 GHz microwave source is about \(50''\) in the north-south scans and \(25''\) in the east-west scans. On the contrary, the polarization distributions change radically with time. At the burst peak, the polarization sense changes from left- to right-circular and then back in the north-south scans. In the east-west scans, a two-polarity structure appears in the time interval around the burst peak.
Fig. 6.—One-dimensional brightness distributions (scans) recorded with the SSRT/EW and SSRT/NS arrays at 5.7 GHz in intensity (left) and polarization (right). Each point in these brightness distributions is the result of integration of the true brightness along a line parallel to the dash-dotted lines shown in Fig. 5. Solid profiles correspond to the burst peak. Profile magnitudes are in arbitrary units. Vertical dash-dotted lines correspond to positions marked in the NoRH map in Fig. 5 (left). The middle panels show the appearance of the unpolarized RS in the north-south scans.
even if the angular distribution of fast electrons is isotropic. The expected presence of a beamlike anisotropy of fast electrons adds a few new free parameters, which further complicate the procedure of the fitting. Therefore, before developing a specific forward-fitting model dealing with gyrosynchrotron emission produced by electron beams, we critically evaluate the observed properties of the burst to restrict or fix as many parameters as possible.

First of all, we make use of the close similarity between the radio and HXR light curves. This similarity suggests that no trapping effect is important in this event and that both HXR and microwave emissions are produced by the same electron distribution. The peak injection rate of electrons above 10 keV derived from the HXR spectrum is \(J(>10 \text{ keV}) \approx 8.5 \times 10^{36} \text{ electrons s}^{-1}\). We take the total number of emitting electrons in the radio source to be \(N_{\text{tot}} = \tau_f J(>10 \text{ keV})\), where \(\tau_f\) is the characteristic lifetime of the emitting electrons in the radio source. Since trapping is not important, we take \(\tau_f\) to be a single, energy-independent free parameter, which will be determined later from the forward-fitting model. It is clear, however, that \(\tau_f\) must not exceed a few seconds, the typical duration of the single pulses that make up the burst. Then, regarding the energy dependence of the electron distribution, we adopt the simplest assumption of a single power law over the momentum modulus, with the spectral index determined from the HXR spectrum (note that the energetic spectral index of 3.4 corresponds to an index of 7.8 in the distribution over momentum). Second, we address the question of what can cause the delay of the HXR emission relative to the microwave emission. If the electron beam is injected somewhere at the top of the loop toward the footpoints, then directly precipitating electrons will first produce the hard X-rays, and a fraction of the electrons reflected back into the loop will later produce the radio emission. Thus, a model involving a directly precipitating beam predicts the opposite delay (HXR leads radio) to what is actually observed. Note that models with electron trapping also predict a delay of radio emission relative to HXR emission (Melnikov 1994).

The only transport model allowing radio to lead HXR emission is a “single reflection” model, which is adopted below. Specifically, if a particle beam with some angular scatter is injected at an asymmetric magnetic trap toward a footpoint with a stronger magnetic field, most of the electrons can be reflected back to form a hollow beam, producing gyrosynchrotron emission in the region of relatively strong magnetic field, and then, after the corresponding travel time over the loop, reach the other footpoint with weaker magnetic field to penetrate deeper into the chromosphere and produce hard X-rays. In this case, the observed delay between radio and HXR originates naturally. In addition, the presence of an initially downward-injected beam is confirmed by the reverse-drifting coherent subbursts (Fig. 3) leading both microwave and HXR peaks by a fraction of a second.

In our event the formation of an asymmetric loop is likely, because the photospheric magnetic field has extremes of \(-170\) and \(+340\) G at the flare kernels K1 and K2, respectively. This means that the magnetic field in the radio source should lie in the range \(+170 \text{ G} < B < +340 \text{ G}\). Indeed, if the regions of weaker magnetic field provided noticeable radio emission, then the trapping of particles between \(-170\) and \(+340\) G loop layers would be important, which is not observed.

Third, the information about the largest possible value of the magnetic field at the source allows us to make a firm conclusion about the possible role of gyrosynchrotron self-absorption in the event. This question is important because the low-frequency slope of the spectrum (\(\gamma = 1.9\)) is consistent with that expected for optically thick gyrosynchrotron radiation (Dulk 1985). However, with the given magnetic field range and the given electron distribution, it is impossible to produce the spectral peak at about 17 GHz (as observed) with the self-absorption effect unless the source is extremely compact, with a linear scale less than 700 km. In this case, however, the number density of fast electrons would exceed \(10^{12} \text{ cm}^{-3}\), which we believe is not realistic. Thus, we take the typical angular scale of the source to be 6″, consistent with imaging observations of the radio source.

Alternatively, a large value of the microwave spectral peak frequency can be provided by the Razin effect, which requires high plasma density at the radio source. Indeed, the presence of such
high density at the source is likely, because we observe type III–like drifting bursts around 5 GHz (Fig. 3). Accordingly, we take the background plasma density to be
\[ n_e = 3 \times 10^{11} \text{ cm}^{-3}. \] (2)

This estimate agrees with the value of the emission measure determined from the soft X-ray emission (Uddin et al. 2004).

In such a dense plasma, the Razin effect is strong over the entire range of the magnetic field, 170–340 G. In conditions of strong Razin effect, the low-frequency slope of the gyrosynchrotron spectrum in a uniform source is much steeper than that observed. We must therefore conclude that the low-frequency slope of the spectrum is eventually formed by a source inhomogeneity, that is, from different layers with magnetic field ranging from 170 to 340 G in the region of kernel K2. In such a dense plasma, free-free absorption is typically important throughout the microwave range (Bastian et al. 2007). However, a high plasma temperature of about 3 \times 10^7 \text{ K} was determined for this event from the soft X-ray data (Uddin et al. 2004); therefore, the free-free optical depth is less than unity at f > 7 GHz. Thus, we will not take into account the free-free absorption in our analysis.

We note that the spectral peak provided by the Razin effect increases as the magnetic field decreases. This means, in particular, that lower frequency emission should arise lower in the loop, in contrast to the usual situation in which higher frequency sources are located lower in the corona. We checked that the position of the brightness peak at 17 GHz is indeed displaced southwest by about 5\' relative to the 34 GHz brightness peak, in agreement with this prediction. Therefore, the high-frequency emission should arise from the region of the lowest possible magnetic field; we thus adopt
\[ B = 180 \text{ G}, \] (3)
consistent with the requirement B > 170 G. Now, with most of the source parameters fixed based on straightforward use of various observational indicators, we can turn to formulating the forward-fitting model.

### 4.2. Forward-fitting Scheme

Even though there are many individual measurements of the radio emission produced by the event under consideration, we can make use of only a minor fraction of them. Indeed, since the low-frequency part of the spectrum is related to the inhomogeneity of the source, which cannot be reliably constrained by the observations, we can only model the high-frequency part of the radio spectrum due to the uniform source (which we refer to as the “high-frequency source”).

Specifically, we assume that the high-frequency source is entirely responsible for the emission at 80 and 35 GHz and for a significant fraction of the emission at 17 GHz. Therefore, we have at best five different observational data points (Stokes I and V at 17 and 35 GHz and Stokes I at 80 GHz), which allow for the finding of four free parameters or fewer. It is clear that the weights of the measurements are different: the highest weight is given to measurements at 35 GHz (5% uncertainty in the intensity, and 10% in polarization), as they have a small experimental error and are expected to be well described by the uniform-source model. The 80 GHz intensity has a lower weight (although it should be described by the uniform model even better than the 35 GHz data, the 80 GHz intensity is measured with 40% uncertainty). The experimental error at 17 GHz is small; however, here the effect of source inhomogeneity becomes important. Thus, we take the high-frequency source to provide 70% of the observed flux at 17 GHz with an uncertainty of 40%; an uncertainty of 100% in the degree of polarization at 17 GHz is adopted.

In the previous subsection, we mentioned that one of the free parameters we determine from the fitting is the characteristic lifetime \( \tau_B \) of the emitting electrons at the radio source. Another important parameter, which is not known from the observations, is the viewing angle \( \theta \) between the line of sight and the direction of the magnetic field at the source, so the viewing angle is the second free parameter in the forward-fitting scheme. Thus, we have to use a test function for the angular part of the electron distribution that depends on only one or two free parameters. Our model involving one reflection of the electrons from the magnetic mirror cannot be described by a function with a single free parameter: it must include both the direction at which the angular distribution reaches a maximum, which differs from the direction along the field lines after the reflection, and the typical angular scatter of the distribution. Thus, a test function with two free parameters is necessary. As the simplest approximation, we adopt a normalized Gaussian angular distribution over the cosine of the pitch angle with unknown mean and dispersion:
\[ f_2(\mu) \propto \exp \left[ -\frac{(\mu - \mu_0)^2}{\Delta \mu^2} \right]. \] (4)

Then we apply a nonlinear code that adjusts the model’s free parameters to minimize the \( \chi^2 \) statistic using the downhill simplex method (Press et al. 1986). The \( \chi^2 \) statistic is calculated as
\[ \chi^2 = \sum_{i=1}^{N} \frac{(S_{obs,i} - S_{mod,i})^2}{\sigma_i^2}, \] (5)
where the \( S_{obs,i} \) are the observational data of either Stokes I or V for the selected three frequencies, the \( \sigma_i \) are defined by the uncertainties introduced above, and the \( S_{mod,i} \) are the model values of the intensity and polarization; \( N = 5 \) for the case at hand.

Our current forward-fitting scheme is different from the scheme applied previously by Bastian et al. (2007) in two respects. First of all, in minimizing the \( \chi^2 \) statistic we employ both intensity and polarization data simultaneously in the same run, which is the first example in which polarization data are used for quantitative diagnostics of the fast-electron distribution. Second, our model function is the exact expression for the gyrosynchrotron emission, including the summation over the series of the Bessel functions and their derivatives. Because the magnetic field at the source is somewhat low, the contribution of large harmonics is important at high frequencies, and therefore we had to use a sum over 1600 terms of the series to describe the emission correctly up to 80 GHz. This made our scheme computationally expensive: the full run for one spectrum took about 50 hr on a PC with a 2.1 GHz processor.

### 4.3. Forward-fitting Results

Given that the observed spectrum does not evolve much during the burst, while the forward-fitting scheme employing the exact gyrosynchrotron equations is very time-consuming, we concentrated our study on the emission at the peak time of the burst (04:03:40 UT) only. The result of the fitting is shown in Figure 8. A number of important things should be noted in this figure. First, the model radio spectra (top left) obtained for the electron energy spectrum derived from the HXR data are a good match to the observed high-frequency part of the radio spectra. Thus, the data are consistent with the model assumption of a
single power-law electron spectrum in the event. Second, the curves for the degree of polarization are very sensitive to the details of the electron angular distribution. In particular, the polarization data are entirely inconsistent with an isotropic angular distribution for the fast electrons, since an isotropic distribution would produce $X$-mode polarized emission, while the observed polarization corresponds to $O$-mode emission. The gyrosynchrotron radiation produced by an oblique beam observed in a quasi-transverse direction is $O$-mode polarized, as needed. The exact value of the degree of polarization depends strongly on the details of the pitch-angle distribution, and thus the joint use of the intensity and polarization measurements is indeed a key to constraining the angular distribution of the electron beam. For the peak time of the burst, the following parameters provide the best fit to the observed spectrum and polarization:

$$\tau_l = 0.45 \text{ s}, \quad \theta = 80^\circ, \quad \mu_0 = 0.5, \quad \Delta \mu = 0.35. \quad (6)$$

All these numbers look reasonable against observations and the theory of gyrosynchrotron radiation from an anisotropic electron distribution. Indeed, the lifetime of the fast electrons is small enough, $\tau_l \approx 0.45 \text{ s}$—that is, less than the radio peak duration, as required. Then, as is known from gyrosynchrotron theory, $O$-mode polarization of the optically thin source is only possible for beam-like electron distributions and for viewing angles larger than the peak angle in the pitch-angle distribution. The obtained values of $\theta$ and $\mu_0$ obey these requirements, since $\cos \theta = 0.16 < \mu_0$.

It is tempting now to subtract the model contribution of the high-frequency source from the observational data points and repeat the forward-fitting procedure. Indeed, we can perform a reasonable fit to the total-power data. As an example, a contribution from a "lower frequency source" with the same pitch-angle distribution but a stronger magnetic field ($B \approx 300 \text{ G}$) and smaller lifetime for the fast electrons ($\tau_l \approx 0.05 \text{ s}$) is shown in the figure. However, it is not possible to perform a consistent fit to the polarization measurements, which is the key to constraining the electron angular distribution, because the observed degree of polarization is essentially the result of averaging various contributions along the nonuniform source. This conclusion is in agreement with the high spatial and temporal variability of the polarization patterns observed at 5.7 GHz, which is most probably a result of changing relative contributions from different parts of an inhomogeneous source (note the very strong frequency dependence of the degree of polarization in the model curves below 10 GHz in Fig. 8). Therefore, the low-frequency observations cannot be conclusively fitted with the uniform-source model.

5. DISCUSSION

In this paper, we have presented a new tool for studying electron beams accelerated during solar flares by analysis of the
gyrosynchrotron emission produced by the beams. Methodologically, this result is achieved by quantitative use of the polarization measurements of the microwave gyrosynchrotron emission. Specifically, to obtain information on the beamlike angular distribution of the accelerated electrons, we developed a nonlinear $\chi^2$ fit employing Stokes $I$ and $V$ measurements simultaneously and the exact gyrosynchrotron formulae.

This approach allows for unambiguous detection of oblique beams at the radio source. In addition, our scheme yields a number of important physical parameters of the radio burst, such as the viewing angle of the radio emission relative to the magnetic field at the source, the characteristic parameters of the electron distribution over pitch angle, and the typical lifetime of the electrons in the radio source (see eq. [6]).

The diagnostics of the electron beam obtained from the fit of the gyrosynchrotron data within the “one-reflection model” are consistent with all other available observations. In particular, the time delay of the hard X-rays relative to the microwaves (a fraction of a second) is consistent with the transit time of electrons with relatively large pitch angles (found from the forward-fitting technique) through the flaring loop, of about $10^4$ km in projection. In addition, the fine structures, consisting of the reverse-drift bursts followed by the normal-drift bursts, detected at about 5 GHz are in agreement with the “one-reflection model,” which implies downward beam propagation followed by a reflection at the magnetic mirror and consequent upward motion of the beam. The radio data suggest that the main radio source is filled by a rather dense plasma (eq. [2]), with a plasma frequency of about 5 GHz. The radio emission observed at lower frequencies (3.75 and 2 GHz) cannot be produced at this main source. The most straightforward interpretation for this low-frequency component is to postulate an adjacent, more tenuous loop where a minor fraction of the accelerated electrons produce lower frequency radiation. Such a larger loop is likely and is confirmed by the presence of a remote source magnetically connected to the main flare site. If so, the larger decay constant and the observed delay of the low-frequency emission relative to the higher frequency emission (see § 3.1) receive a natural interpretation because they simply relate to the larger source size, implying a longer transit time, where in addition some trapping of the electrons can be important.

Another possible effect of the dense plasma is an enhanced role of Coulomb collisions for the radiating electrons. Given the relatively low value of the magnetic field at the source, it is easy to estimate the typical energies of the radio-emitting electrons as $1-10$ MeV, which have a Coulomb energy decay time $\tau_C > 15$ s, much longer than the transit time. The time for isotropization of these relativistic electrons due to Coulomb collisions is even longer than the energy decay time (Petrosian 1985). We thus conclude that Coulomb collisions have very little effect on the electron distribution on the timescale of the electron precipitation ($\sim 1$ s) in this event.

Although we quantitatively describe the emission at the burst peak only, we can reliably extrapolate the main findings, such as acceleration of the fast electrons in the form of beams and the one-reflection transport model, to the entire burst duration. This follows from the close similarity between the radio and the hard X-ray light curves and from the constancy of the sense of polarization in the main source at 17 GHz. This means that some flares, such as the one considered here, can predominantly accelerate electrons along magnetic field lines even though the pitch-angle distribution of the beam has some angular scatter.

The potential of the developed method is very strong, and it will be especially helpful when imaging spectroscopy data are available. However, routine use of this method will require optimization of the computational scheme, which is not fast enough at present. Therefore, deducing simplified, although precise enough, gyrosynchrotron formulae for anisotropic electron distributions would be very helpful here.

6. CONCLUSION

Electron beams with some angular scatter can efficiently produce microwave continuum bursts through the gyrosynchrotron mechanism. As was shown theoretically by Fleishman & Melnikov (2003), the gyrosynchrotron emission produced by electron beams can be distinguished from that produced by isotropic electron populations through analysis of the degree of polarization of the microwave emission. Here we presented a compelling example of such an event, where the optically thin gyrosynchrotron radiation is indeed $O$-mode polarized as expected for a beamlike distribution. Remarkably, the presence of the beam is confirmed by the whole set of available data for this event.

In the case of radio data of good enough quality (including both intensity and polarization), the use of forward-fitting inversion methods allows for determination of quantitative diagnostics of the fast-electron angular distribution, as well as a number of other important physical parameters of the flaring source. These methods will become much more useful when imaging spectroscopy data are available.

The authors express appreciation to Professors Kiyoto Shibasaki and Hiroshi Nakajima for the NoRP calibration corrections they provided. This work was supported in part by NSF grants AST-06-07544 and ATM 07-07319 to the New Jersey Institute of Technology, by the Russian Foundation for Basic Research, grants 06-02-16295, 06-02-16859, 06-02-39029, and 07-02-01066, and by National Natural Science Foundation of China grant 10333030 and the “973” Program (No. 2006CB806302). We have made use of NASA’s Astrophysics Data System Abstract Service.

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