A microflare with hard X-ray-correlated gyroresonance line emission at 314 MHz

H. Aurass¹, G. Rausche^{1,3}, S. Berkebille-Stoiser², and A. Veronig²

¹ Astrophysikalisches Institut Potsdam (AIP), 14482 Potsdam, Germany
e-mail: haurass@aip.de

² Physikalisches Institut der Universität Graz, 8010 Graz, Austria

³ Gymnasium der Ludwig-Geissler-Schule Hanau, 63450 Hanau, Germany

Received 17 August 2009 / Accepted 18 December 2009

ABSTRACT

Context. Small energy release events in the solar corona can give insights into the flare process which are regularly hidden in the complex morphology of larger events. For one case we find a narrowband radio signal well correlated with the hard X-ray flare. We investigate whether these signals are probes for the flare current sheet.

Aims. We aim to establish the relation between narrowband and short-duration features ($<1\%$ of the observing frequency in the spectral range 250–340 MHz, and some 5 s until 2 min, respectively) in dynamic radio spectral diagrams and simultaneously occurring HXR bursts.

Methods. We use dynamic radio spectra from the Astrophysical Institute Potsdam, HXR images of RHESSI, TRACE coronal and chromospheric images, SOHO-MDI high resolution magnetogram data, and its potential field extrapolation for the analysis of one small flare event in AR10465 on September 26, 2003. We point to similar effects in e.g. the X-class flare on November 03, 2003 to demonstrate that we are not dealing with a singular phenomenon.

Results. We confirm the solar origin of the extremely narrowband radio emission. From RHESSI images and the magnetic field data we identify the probable site of the radio source as well as the HXR footpoint and the SXR flare loop emission. The flare loop is included in an ongoing change of magnetic connectivity as confirmed by TRACE images of hot coronal loops. The flare energy is stored in the nonpotential magnetic field substructure around the microflare site which is relaxed to a potential one.

Conclusions. We conclude that the correlated HXR footpoint/narrowband radio emission, and the transition to a second energy release in HXR without associated radio emission are direct probes of changing magnetic connectivity during the flare. We suppose that the narrowband radio emission is due to gyroresonance radiation at the second harmonic of the local electron cyclotron frequency. It follows an upper limit of the magnetic field in the radio source volume of less than 50% of the mean potential field in the same height range. This supports the idea that the narrowband radio source is situated in the immediate surroundings of the flare current sheet.

Key words. Sun: corona – magnetic fields – Sun: flares – Sun: radio radiation – Sun: X-rays, gamma rays

1. Introduction

During solar flares, a part of the energy leaves the release site via energized (nonthermal) electrons. During the propagation through the coronal plasma the electrons excite plasma waves. The plasma waves are unable to leave the corona but can be nonlinearly transformed into bright electromagnetic radiation (Zhelesnyakov 1996), which is recorded as a nonthermal solar radio burst on earth. A well-known example are type III radio bursts excited by electron beams guided along the magnetic field. Energetic electrons in a closed field configuration precipitate into denser layers of the corona and/or are trapped in the field. Precipitation results in nonthermal microwave- and hard X-ray burst emission. Further, it leads together with heat conduction along magnetic field lines to chromospheric heating and evaporation. This is visible in the chromospheric UV continuum and the $H\alpha$ line emission as well as in coronal soft X-rays and EUV lines.

The analysis of dynamic radio spectra obtained with sensitive spectrometers shows that as a rule the very first flare burst signatures occur at ≈ 300 MHz¹. This observational experience

fits with the prediction of a preferred window of not too high coronal densities and not too low magnetic fields² for nonthermal flare energy release conditions (Spicer 1977).

The flare energy is slowly accumulated in coronal magnetic field structures due to its reaction to subphotospherically driven footpoint motions and/or magnetic flux changes. Field structures contain flux cell boundaries which have an extreme sensitivity for disturbances – speaking in field line terms: small changes at one field line footpoint lead to a strong change at the other footpoint. Such a connectivity change is accompanied by current sheet (CS) formation. It is generally accepted that magnetic reconnection at flare CS is a probable mechanism of coronal energy release (Somov 2000).

As mentioned, nonthermal electrons in closed fields can be trapped and radiate broadband radio continua, frequently occurring in strong and complex type IV bursts as well as during noise storms (Dulk et al. 1985). Sometimes, the smooth continuum is the background of spectral fine structures – the dynamic spectra show patterns of small-scale³ bright and dark

¹ This means an electron density of 10^9 cm⁻³ for fundamental mode and 3×10^8 cm⁻³ for harmonic mode plasma emission.

² The 300 MHz level is situated not higher than several 10 Mm in active region density models.

³ bandwidth $\approx 1\%$ of the observing frequency, duration subseconds to some seconds.

regions. They occur as a consequence of secondary processes in the continuum source volume, e.g. loop collisions (Khan & Aurass 2006), whistler wave propagation (Benz & Mann 1998), double-plasma-resonance of bouncing electrons (Zlotnik et al. 2003), or simply injection of a new electron ensemble (Zlotnik et al. 2009).

To our knowledge, single meter wave spectral lines of solar origin have only been reported by Klassen et al. (2001) as spectral features organized in “sawtooth pattern”. In full-disk broadband spectrometry the recognition of radio spectral lines is difficult because a lot of terrestrial disturbances occur as “lines” in the spectrum. In the microwave range, spectral lines were reported by Bogod et al. (1998). Plasma emission acting in the high density case (plasma frequency $f_p \gg$ cyclotron frequency f_c)⁴ and gyroresonance emission acting in the low density case ($f_p \ll f_c$) are radiation mechanisms for extreme narrowband radio phenomena (Dulk et al. 1985).

Here we present a case of extreme narrowband radio emission discovered in the decimeter-/meterwave range (at 314 ± 1 MHz) in AR10465 on September 26, 2003 during a microflare (Sect. 2). Microflares are small flares containing roughly a millionth part of the thermal energy observed in very large flares (Aschwanden 2006). Several such small events were only recently mapped with the RHESSI instrument on September 26, 2003 for which observation a highly resolved SOHO/MDI magnetogram is available. A detailed description and an extensive analysis of several more microflares on this day can be found in Stoiser et al. (2007). Aurass et al. (2009) analyze the magnetic field structure of two microflares with radio signatures in the meter wave range. One of these radio events starts at 12:04 UT (our event of interest, EOI) in close correlation with the growth of the hard X-ray (HXR) flux. We noticed similar spectral features in phase with early HXR energy release signatures in a more complex event (Sect. 2.2). This demonstrates that we are not analyzing an exotic and perhaps nonsolar case with accidental radio-HXR-correlation. In Sect. 3 we demonstrate that in the present case the source volume of the narrowband radio emission must be situated in the immediate surroundings of the primary flare energy release site.

In this work we take advantage of the high sensitivity of the radio spectrometer of the Astrophysical Institute Potsdam (AIP, Mann et al. 1992)⁵. The dynamic radio spectrum is compared with the X-ray observations of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Further we apply SOHO observations of the longitudinal magnetic field in the photosphere by the Michelson Doppler Imager (MDI) and observations by the Transition Region and Coronal Explorer (TRACE, the ultraviolet images at 171 and 1600 Å). The same data sources are used in Stoiser et al. (2007), corresponding references are given there.

2. Data analysis

2.1. Why microflares?

There is the old question whether microflares are part of a cascade of energy release processes which downscale to coronal heating at the microscopic level (e.g. Aschwanden 2006).

⁴ $f_p = \sqrt{e^2 N_e / \pi m_e}$; $f_c = eB / 2\pi m_e c$, N_e —electron density, e —elementary charge, m_e —electron mass, c —speed of light, B magnetic field strength.

⁵ The range 200–400 MHz is observed with a 7.5 m diameter parabolic aerial.

Stoiser et al. (2007) have recently reanalyzed that question based on RHESSI HXR- and TRACE (UV continuum, EUV line) images, and on SOHO-MDI observations with 0.6 arcsec pixel size (high resolution campaign). They found that all microflares that could be imaged by RHESSI were concentrated in one active region (AR10465) and that rough estimates of their energy content were small compared with active region losses. The authors noticed that some microflares show faint signatures in dynamic radio spectra (data of Astrophysical Institute Potsdam). This is not surprising because according to the HXR spectra a considerable part of the released energy is transferred into nonthermal electrons, as is also the case for larger flare events. The nonthermal electrons, propagating in the coronal plasma, excite plasma waves which can nonlinearly convert into transversal waves able to leave the plasma as radio burst emission. The radio spectra are at first glance simple and well known (e.g. type III bursts, a faint type II burst lane etc.). They are not nearly as complicated as the patterns observed in strong flare events.

2.2. The radio/HXR association and the solar origin of the effect

During the microflare of GOES class B1.1 starting at 12:04 UT (EOI in this paper) we found a new feature in the dynamic radio spectrum. Its radio flux is highly correlated with the HXR flux during the first 80 s of the event. Figure 1a shows the radio spectrum with a strong, narrowband gradual rise and fall emission at 314 MHz (bandwidth $<1\%$ of the observing frequency, see also the instantaneous spectrum in Fig. 1a, right) and for a 2 min duration. The duration of this emission is over one order of magnitude larger than for other narrowband radio phenomena (type I bursts, spikes). It is most comparable with a single line of a zebra pattern⁶, but without any associated continuum emission. The gradual flux-over-time curve alone distinguishes this signal from a terrestrial disturbance with its sharp switch-on/switch-off profile. We call the signal a “radio line” (RL) in this paper. Superposed at 12:05:36–38 UT a pair of type III bursts occur in the spectrum between 400 and 40 MHz and in the 314 MHz radio flux curve (Fig. 1). The AIP spectral observations are not calibrated in solar flux units⁷. But we can determine the flux of the type III burst source at 314 MHz which is almost equal to the flux of the line emission at 12:05:38 UT (Fig. 1b). This is done by interpolating the type III burst flux values obtained by the Nançay Radio Heliograph (NRH) at 327 and 236.6 MHz. The result is a 314 MHz flux density of 5.5 sfu. Because of the logarithmic scale of the AIP spectrometer, the RL maximum flux is at least one order of magnitude larger.

Considering Fig. 1b a lag seems to be obvious between the radio and the X-ray data (radio seems to lead X-rays). But we are not sure about the significance of the delay, it exists only during the rise phase but not in the beginning or during the maximum of the signals. For the moment we will not speculate about this effect, as we also bear in mind that the X-ray variability could be undersampled.

Contrasting with the RL, the hard X-ray burst consists of two overlapping enhancements of a comparable time scale, where the second one is not accompanied by radio emission except for the already mentioned type III bursts. We come back to this remarkable fact later on.

⁶ Zebra patterns can have even longer durations, see e.g. Chernov (2006).

⁷ 1 sfu = 10^{-22} W m⁻² Hz⁻¹.

Fig. 1. The GOES B1.1 microflare in radio (AIP) and hard X-rays (RHESSI). **a)** The radio spectrum with a spectral line at 314 ± 1 MHz. The later effects at ≈ 342 MHz are characteristic terrestrial disturbances. *Right:* instantaneous radio spectrum at line flux maximum. **b)** The radio flux profile at 314 MHz and the time-aligned 15–20 keV count rates of the source shown in Fig. 3. The count rates are normalized to 1, the radio flux is normalized to 0.8 for best (subjective) coincidence of both curves.

Here we stress that an RL is not a unique and singular phenomenon in the frequency range of 250–340 MHz during the impulsive rise of HXR emission. We have noticed it already during several stronger flares. As an example, Fig. 2 gives the X-class flare of 03 November 2003 which occurred at the northwest limb (Dauphin et al. 2006; Veronig et al. 2006). During that event a revival of the energy release occurred (a so-called late energy release, Fig. 2a, see also Warmuth et al. 2009) after the first impulsive HXR rise in the 100–300 keV energy range. Associated with the first pulse of both HXR enhancements (here: 9:49:24 and 9:57:00 UT) an RL appears in the spectrum at 285–280 MHz and 275–305 MHz, respectively. In both cases the RL has a duration of 10–15 s (Fig. 2b and c, letters A and E) and is a minor spectral detail among many other features. It has the same bandwidth as in the microflare RL, but shows a slowly varying center frequency: in case (b) decaying by 1%, in (c) rising by $\approx 10\%$ of the frequency. The above mentioned delay problem cannot be studied here because of the complexity of the event – there is no detailed morphological resemblance between components in X-ray and radio emission, and the relatively faint RL is embedded among other spectral features with possible HXR equivalence.

The most important new finding of the microflare case is the certain solar origin of the RL, thanks to the simplicity of the flare, the smooth line profile in time and frequency, and the simultaneous occurrence and correlation with the first HXR impulse (Fig. 1).

We focus now on the reconstruction of a large-scale flare scenario for the microflare and on the information from the combined radio/HXR data about the electron acceleration in the EOI. A correct quantitative discussion of the RL emission is beyond the scope of this work. We stress that the narrowband RL is not visible with the Nançay Radio Heliograph (NRH) observing at 327 and 236.6 MHz. There is imaging information for the simultaneously recorded hard X-rays, only.

2.3. Imaging information

In Fig. 3 the HXR emission of the EOI is overplotted on a TRACE 1600 Å image associating HXR sources with chromospheric UV continuum emission. The X-ray contour lines are obtained by integrating over the time of the first and the second pulse, respectively. For the first pulse (but not for the second!) we are able to reconstruct an image in the 12–25 keV range (Fig. 3a), which is concentrated on the northern part of the 3–8 keV image (Fig. 3b). The 12–25 keV map shows a source with two maxima roughly situated at two UV flare brightenings. They are part of the flare ribbons with NE-SW inclination coincident with an inverted S-shaped EUV loop visible during the flare onset (see Fig. 6, 12:04:54 UT). In the 3–8 keV range, only the outer HXR isoline (20% of the maximum level) encloses the whole southern flare ribbon. Note that this ribbon is a very bright dot-like feature in the chromospheric emission.

Fig. 2. The X-class flare of 03 November 2003 – an extremely strong flare with two radio line (RL) occurrences near 300 MHz. **a)** The RHESSI HXR flux with at least two distinct energy release stages. Vertical bars denote the RL time in the AIP radio spectra marked by A and E in panels b and c.

From the contrasting radio-HXR association between the first and the second HXR pulse (Fig. 1) we conclude that if both HXR enhancements are due to the same electron accelerator, the nonthermal electrons in the first enhancement are in a very specific manner confined and thus emit the RL. There is no confinement for the electrons inducing the second HXR enhancement without a radio signature.

The presence of an isotropic ensemble of accelerated electrons at the loop top leads to the trapping of the quasi-perpendicular component in this region. The quasi-parallel component starts to bounce and precipitate to the loop footpoints. If the density and magnetic field changes are small near the loop top, the nonthermal electrons can be the source of the narrow-band radio emission (Zlotnik & Sher 2009) while the precipitating electrons lead to the HXR footpoint emission. From the absence of radio emission during the second HXR pulse we argue that the magnetic structure which guides the energetic electrons has been disrupted between the first and the second HXR peak. The occurrence of type III bursts near the beginning of the second HXR enhancement supports this assumption. Aurass et al. (2009) describe the type III source sites at 327 and 236.6 MHz as distant from the HXR sources. This is not surprising if the type III burst electrons are injected in a dynamically changing magnetic field just during the field reconfiguration.

RHESSI spectra indicate that the 3–8 keV emission expresses thermal emission (see Fig. 5), whereas radiation with energies of ≥ 12 keV is dominated by nonthermal bremsstrahlung during both bursts. The HXR images are almost similar in both energy ranges during the second burst. The spectral fits plotted in Fig. 5 reveal an energetic electron precipitation rate ($E > 10$ keV) of $1.1 \times 10^{35} \text{ s}^{-1}$ for the first HXR impulse, based on a thermal plus thick target bremsstrahlung model of X-ray emission (Brown 1971). The second HXR burst corresponds with a slightly reduced precipitation rate of $0.8 \times 10^{35} \text{ s}^{-1}$.

According to the isoline plot in Fig. 3 the HXR source centroid is situated in a magnetic loop with a footpoint spacing of ≈ 13 arcsec. If we take that extent as the source height (9.5 Mm), we obtain with a plasma frequency of 314 MHz⁸ a slightly enhanced coronal density ($1.6 \times \text{Newkirk 1961}$). This estimate supports the statement that the observed active region AR10465 is simply structured, in the sense of a small density enhancement compared with quiet Sun coronal conditions. Figure 4 shows the SOHO-MDI magnetogram of AR10465 with a well-defined leading and following spot (arrows). All microflares in the Stoiser et al. (2007) study occur in the space between the main spots and in heights below 20 Mm. The region of interest (ROI) shown in Figs. 3 and 6 is enclosed by a box in Fig. 4.

A potential field extrapolation was carried out after integrating the MDI observations from 0.6 to 1.2 arcsec/pixel. The result confirms that in heights above 100 Mm both the main spots (arrows in Fig. 4) determine a simple bipolar configuration (see Aurass et al. 2009).

Figure 6 shows the EOI in TRACE 171 Å (right column) and the corresponding part of the SOHO-MDI magnetogram (the box in Fig. 4). In the magnetogram we overplotted selected field lines of the potential field extrapolation. The flare brightenings in the TRACE 1600 Å images served as selection criterion. Early in the flare, the potential field does not reflect the bright coronal structures, in contrast with the situation in the postflare phase (the two bottom rows of the figure). Thus, the transition of the stressed (nonpotential, preflare) field structure into a relaxed (potential, postflare) field can well be quite locally the source of the flare energy.

The field relaxation can be reconstructed via considering a quadrupolar source configuration. For this purpose we sketch in Fig. 7 those coronal loops which are significant in Fig. 6 to compare the time intervals 12:04 and 12:22 UT (the impulsive and the postflare phase). Flare-relevant field concentrations $> 10^3$ Gauss are denoted as R1, B1, and R2, B2 in Fig. 7. From

⁸ And, for the moment assuming plasma emission of the RL.

Fig. 3. TRACE 1600 Å continuum and RHESSI HXR overlaid. North is top, East is left, as in all following solar images. **a)** 90, 70, 50 and 30% isolines of 12–25 keV integrated in 12:03–12:05:20 UT (Fig. 1, first pulse). **b)** 90, 50, and 20% isolines of 3–8 keV integrated in 12:05:20–12:06:20 UT (Fig. 1, second pulse). Both TRACE images are normalized on their brightness maximum.

Fig. 4. High resolution SOHO-MDI magnetogram 04:00:03 UT. The box encloses the ROI shown enlarged in Figs. 3 and 6. Arrows point on the leading and the following main spot.

Fig. 3 it is evident that the trailing UV continuum flare ribbon extends between B2 and B1. The leading somewhat discontinuous ribbon spans from west over north to east and encloses the flux concentration R1.

In the preflare phase the magnetic configuration consists of two dominating arcades in the quadrupolar source field. Both arcades are connected by a common inverted-S-shaped flare loop which connects B2 with R1. In the postflare phase, the preflare connections R1–B2 and R2–B1 are transformed as follows: a long and only faintly inverted S-shaped connection brightens between R1 and B1. Shorter connections become visible between R1 and B2. Additionally we recognize a R2–B1 and perhaps also R2–B2 connection. New westward extensions from range B1–B2 also occur.

3. Discussion

3.1. Where is the flare current sheet?

A top view on a scheme of the essential *preflare* loops drawn according to Fig. 7a is given in Fig. 8a. A characteristic feature visible in the early coronal flare loops is the arcade that bridges the magnetic neutral line with a kinked NS-axis. At the southern end of the arcade the footpoint spacing of bright loops jumps from 5 arcsec at B1 to more than 15 arcsec between B1 and R2.

This sketched quadrupolar magnetic field configuration enabling the microflare vividly recalls of an example of a linear source arrangement discussed by Somov (2000). In our case the magnetic flux concentrations are distributed in a plane forming a linear arrangement in the side view only (from the West in Fig. 8b). The dashed field line drawn in Fig. 8b is the postflare connection B1–R1 which is formed by reconnection between a loop B1–R2 and a shorter loop B2–R1.

The HXR double footpoint source in Fig. 3 and the HXR-radio flux coincidence in Fig. 1 show that a common electron accelerator (e.g. the flare CS) must be situated near to the HXR source centroid *between* the footpoint sources. On the other hand, the extremely narrow bandwidth of the RL points to a very small radio emission source volume. Density estimates derived from the X-ray data (Stoiser et al. 2007) are roughly one order of magnitude larger than those derived from the radio line frequency, at least. Because the rising HXR emission still comes from flare loops not yet filled with evaporated matter the density difference is an argument to assume the electron accelerator site above the flare loop top with the X-ray footpoint sources. This fits well with our sketch of Fig. 8 where the reconnection site (the flare CS) is shaded, and the HXR footpoint sources are situated next to the magnetic flux concentrations R1 and B2. In other words the RL source volume is next to the flare electron accelerator. Its signature in the dynamic spectrum allows access to the reconnection dynamics at the flaring CS.

There are reports about large spatial distances between decimetric radio sources and radio flux-correlated HXR sources (Khan & Aurass 2006; Battaglia & Benz 2009). However, these authors studied *clouds* of spike burst emission, a phenomenon with a patchy broadband morphology in the dynamic spectrum. It is only possible to compare frequency- and/or time integrated radio data with the less time-resolved HXR flux curves, which says nothing about the correlation of a single spike burst profile in the radio and the HXR radiation. We are in a better position, here. We can summarize our considerations as follows:

- in the “preflare” magnetic configuration, and during the first HXR pulse, we hypothesize that the RL reflects the growth of the current in the CS accompanied by an *isotropic* ensemble of energized electrons. The quasi-parallel electrons produce the HXR footpoint emission during its precipitation while the RL is emitted because of the quasi-perpendicular component of the injected electrons captured near the loop top. The current growth leads to loop and footpoint heating as well as to particle acceleration, and is sustained for at least

Fig. 5. Two X-ray photon spectra reconstructed for 16 s during **a)** the first and **b)** the second peak in the RHESSI 15–20 keV light curve of the EOI (Fig. 1). The spectra were fitted with a thermal (light grey solid line) plus a thick target bremsstrahlung model (grey dot dashed line). The sum of both components is shown as a thin solid line. Emission measure EM , temperature T and electron spectral index δ of a thick target fit are indicated in the plots. The spectra were derived using the *Ospex* package (Schwartz et al. 2002) and with all detectors except 2 and 7. The pre-event background was subtracted.

1 min (12:04–12:05 UT, Fig. 1). All this preceeds the current disruption;

- the type III bursts (Fig. 1, 12:05:36–38 UT) indicate the escape of accelerated electrons after the opening-up of the preexisting trapping structure. Consequently there is no RL afterwards, although the presence of non-thermal precipitating electrons is indicated by a nonthermal component in the RHESSI spectra (Fig. 5) of the second HXR burst;

- the time scale of the whole field reconfiguration and efficient electron acceleration amounts to 2 min;

3.2. How to interpret the radio line?

As already mentioned in Sect. 1, considering narrowband radio phenomena, we find type I bursts and type IV burst fine structure emission (Dulk et al. 1985) in the decimeter and meter wave range. A short duration and a narrow bandwidth point to small source volumes. Radiation temperature estimates show that this is several orders of magnitude above the coronal plasma temperature. Therefore narrowband radio signals are coherent emissions powered by nonthermal electrons. There are no reports about the emission of isolated⁹ radio spectral lines in the decimeter and meter wave range except by Klassen et al. (2001), who found sawtooth patterns in dynamic spectra of the impulsive phase of complex flares associated with impulsive HXR emission. The authors note that the morphology of that signal corresponds with the X-ray and the electron cyclotron line signal observed shortly before the destructive “sawtooth collapse” in the Tokamak plasma (Biskamp 2000), indicating electron temperature variations and complex motions of the heated plasma. On the Sun, small cores of hot plasma (e.g. X-ray emission of hot loops filled with flare plasma) are “... the simplest object which may exhibit distinct lines at cyclotron harmonics.” (Zhelesnyakov 1996, p. 284). We expect that the energy release site of the analyzed microflare is such a “simple object”.

In the EOI we can estimate the magnetic field in the source region of the HXR emission centroid. For this purpose we calculated an average field line (Rausche et al. 2007, for the definition) of 27 potential lines with arclengths <40 arcsec between the field concentrations R1–B2. The result is shown in Fig. 9. We find in the expected flare height average field values >140 Gauss (electron gyrofrequencies >390 MHz).

Zhelesnyakov & Zlotnik (1980) used a CS model to calculate its thermal cyclotron line emission; Fig. 10 sketches the behaviour of density and magnetic field over the abscissa z perpendicular to the length axis of a CS with the thickness $2l$ and with the background parameters indexed by zero. A CS is characterized by huge density and magnetic field gradients on small spatial scales perpendicular to the length axis L of the CS (sheet thickness $2l \approx$ meters at coronal conditions). In the center of the CS there is a density maximum and a magnetic field reversal. If this model holds it is well possible that the RL is a cyclotron line emitted by a volume with a plasma frequency somewhat below 314 MHz (remember the sharp bandwidth!). Suppose the surrounding plasma frequency is 10% below the RL frequency, ≈ 280 MHz. Using a $1.2 \times$ Newkirk (1961) density model, the height of this level is at 6 Mm well in the range of the potential field line turning point heights between R1 and B2 (Fig. 9). Now we can estimate an upper boundary of the magnetic field strength in the source of the RL.

Flare-accelerated electrons excite upper hybrid plasma waves which can be nonlinearly transformed into radio waves at the same frequency or at the harmonic mode. The upper hybrid waves propagate dominantly perpendicular to the magnetic field and are excited at the frequency

$$f_{UH} = \sqrt{(f_p^2 + f_B^2)}, \quad (1)$$

with the maximum growth rate at

$$f_{UH} = s \times f_B \quad (2)$$

⁹ On the frequency axis.

Fig. 6. *Left:* SOHO-MDI magnetogram of the ROI in Fig. 4. Overplotted: potential field lines (after Aurass et al. 2009) selected by means of TRACE 1600 Å-bright pixels. *Right:* TRACE 171 Å bright coronal pre- and postflare loop patterns. The coronal bright loops fit with the potential field in the postflare phase (the two bottom rows). TRACE data are corrected to the magnetogram observing time.

(the double plasma resonance condition, e.g. Zlotnik & Sher 2009).

Let us now take $f_{UH} = 314$ MHz (the frequency of the narrowband radio emission) and $s = 2$ (the smallest possible s -value). We obtain a gyrofrequency of $f_B = 157$ MHz corresponding to a magnetic field of 56 G, and a plasma frequency $f_p = 272$ MHz.

This is an upper field boundary because s can be higher and the plasma frequency can only be smaller. From the reference magnetic field data (potential field, Fig. 9) representing the *postflare* situation, the average loop top field strength is ≈ 140 G. It follows, that in the radio source volume of the narrowband emission the magnetic field is at least 50% below the surrounding average *postflare* (!) magnetic field. This is well possible at a

Fig. 7. SOHO-MDI magnetogram of the ROI in Fig. 4. Letters denote a quadrupolar field configuration. Dominant loop structures are overplotted after visual inspection of the TRACE 12:04 and 12:22 UT 171 Å images. **a)** The nonpotential preflare state. **b)** The potential postflare state (compare Fig. 6).

coronal CS (Fig. 10), and supports our thesis that the RL source site is situated at the microflare CS.

Taking a CS width of 1 m, its observable area is $\leq 10^{-3} \times L$, with L [km] the CS length. Using further an event duration of 2 min, and an RL bandwidth of 2 MHz, we can transform an average event flux of 5.5 sfu (see Sect. 2.2) in a mean brightness temperature $T_{\text{bright}}[\text{K}] > 9 \times 10^{12} \times L[\text{km}]$. This high value additionally points to a coherent radiation mechanism.

4. Conclusion

During a microflare observing campaign (Stoiser et al. 2007) we found a remarkable narrowband radio emission feature (RL) in the meter wave range which we have previously noticed only in the impulsive phase of several strong flares. Here we present this observation and can beyond doubt prove its solar origin for the first time thanks to the morphological simplicity of the dynamic radio spectrum and the evident correlation with the 15–20 keV HXR flux.

Consequently, we have analyzed the data set of the radio and the UV coronal line and chromospheric continuum observations

Fig. 8. The simplified magnetic preflare (!) situation for the ROI. **a)** Top view. **b)** Side view from the West. Shaded: the region with the flare current sheet (CS) with the length L and the thickness $2l$ acting during the impulsive phase. The connection B1–R1 formed by re-connection is dashed and inserted in the side view, only, for simplicity.

Fig. 9. The average potential field R1–B2 along field lines shorter than 40 arcsec. z is the height over the photosphere.

Fig. 10. Scheme of density N and magnetic field B vs. the surrounding reference values N_0 and B_0 drawn over an axis z perpendicular to the length axis of a CS of a thickness $2l$, after Zhelesnyakov & Zlotnik (1980). $z = 0$ is the center of the CS.

together with a high resolution SOHO-MDI magnetogram and its potential field extrapolation.

The microflare energy originates in a nonpotential coronal magnetic field configuration. This is shown by the comparison of the TRACE 171 Å images of bright coronal loops with field lines of the potential field extrapolation which fit in the post-flare phase, but not in the impulsive phase. The HXR source

centroid position shows a loop with HXR footpoint sources of almost equal strength. The X-ray source position compared with the pre- and postflare loops and the correlation between a primary hard X-ray signal and the narrowband RL observed at 314 MHz support the assumption that both signals are probes of microflare current sheet parameters. The missing radio-HXR association during a second HXR enhancement can be understood by the current disruption at the primary energy release site and the meanwhile changed magnetic connectivity. This agrees well with the occurrence of type III bursts due to flare electrons escaping along opened field lines at the beginning of the second HXR enhancement.

As to the emission mechanism of the radio line, we suggest cyclotron line emission due to the double plasma resonance effect at the second harmonic of the local electron gyrofrequency. Based on our analysis we can estimate an upper boundary for the magnetic field in the source volume of the RL. We obtain a value $<50\%$ of the potential field strength and take this as an additional argument for the thesis that the RL source volume is a probe near the microflare current sheet.

Acknowledgements. We acknowledge the use of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), the SOHO Michelson Doppler Imager (MDI), and the Transition Region and Coronal Explorer (TRACE). SOHO is a project of international cooperation between ESA and NASA. We gratefully acknowledge the open access to the Nançay Radio Heliograph imaging data and to the Astronomical Institute Ondřejov radio spectral data. The suggestions of an unknown referee improved this work.

H.A. and G.R. thank Dr. G. Mann for his support and permanent interest. G.R. held the grant by AU 106/13-2 (2006–2008, Deutsche Forschungsgemeinschaft). H.A. thanks the International Space Science Institute, Berne (ISSI) for the hospitality provided to the team *Role of Current sheets in Solar Eruptive Events*. S.B.-S. was supported by an ESO travel grant for students.

References

- Aschwanden, M. 2006, *Physics of the Solar Corona* (Berlin: Springer)
- Aurass, H., Rausche, G., Hofmann, A., Stoiser, S., & Veronig, A. 2009, *Centr. Europ. Astrophys. Bull.*, 33, 159
- Battaglia, M., & Benz, A. O. 2009, *A&A*, 499, L33
- Biskamp, D. 2000, *Magnetic Reconnection in Plasmas* (Cambridge: Cambridge Univ. Press)
- Benz, A. O., & Mann, G. 1998, *A&A*, 333, 1034
- Bogod, V., Garaimov, V., Zhelesnyakov, V., & Zlotnik, E. Ya. 1998, in *Solar Physics with Radio Observations*, Proc. Nobeyama Symp., NRO Rep., 479
- Brown, J. C. 1971, *Sol. Phys.*, 18, 489
- Chernov, G. 2006, *Space Sci. Rev.*, 127, 195
- Dauphin, C., Vilmer, N., & Krucker, S. 2006, *A&A*, 455, 339
- Démoulin, P., Bagala, L. P., Mandrini, C. H., Henoux, J. C., & Rovira, J. V. 1997, *A&A*, 325, 305
- Dulk, G. A., McLean, D. J., & Nelson, G. J. 1985, in *Solar Radiophysics*, ed. D. J. McLean, & N. R. Labrum (Cambridge: Cambridge Univ. Press), 53
- Khan, J. I., & Aurass, H. 2006, *A&A*, 457, 319
- Klassen, A., Aurass, H., & Mann, G. 2001, *A&A*, 370, L41
- Mann, G., Aurass, H., Voigt, W., & Paschke, J. 1992, *ESA SP-348*, 129
- Newkirk, G. A. 1961, *ApJ*, 133
- Rausche, G., Aurass, H., Mann, G., Karlický, M., & Vocks, C. 2007, *Sol. Phys.*, 245, 327
- Schwartz, R. A. 2002, *Sol. Phys.*, 210, 165
- Somov, B. V. 2000, *Cosmic Plasma Physics* (Dordrecht: Kluwer) 574
- Spicer, D. S. 1977, *Sol. Phys.*, 53, 305
- Stoiser, S., Veronig, A. M., Aurass, H., & Hanslmeier, A. 2007, *Sol. Phys.*, 246, 339
- Veronig, A. M., Karlický, M., Vršnak, B. et al. 2006, *A&A*, 446, 675
- Warmuth, A., Holman, G. D., Dennis, B. R. et al. 2009, *ApJ*, 699, 917
- Zhelesnyakov, V. V. 1996, *Radiation in Astrophysical Plasmas* (Dordrecht: Kluwer)
- Zhelesnyakov, V. V., & Zlotnik, E. Ya. 1980, *Sol. Phys.*, 68, 317
- Zlotnik, E. Ya., & Sher, É.M. 2009, *Radiophys. Quant. Electr.*, 52, 88
- Zlotnik, E. Ya., Zaitsev, V. V., Aurass, H., Mann, G., & Hofmann, A. 2003, *A&A*, 410, 1011
- Zlotnik, E. Ya., Zaitsev, V. V., Aurass, H., & Mann, G. 2009, *Sol. Phys.*, 255, 273