Coherent Radio Emission of Solar Flares in the Decimeter Range (0.3–3 GHz)

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Abstract. Whereas metric solar radio bursts have been observed since 40 years and flare gyro-synchrotron emission peaks usually beyond about 5 GHz, the flare emissions in the decimetric range have been thoroughly investigated only recently, the 1–3 GHz range in the past six years.

Most frequent is a broadband, short emission that rapidly drifts to higher or lower frequency. It has all the properties of the beam-plasma radiation (type III burst) at metric wavelengths except that it does not continue to lower frequencies. Flares with hundreds of such bursts have been observed. The more prominent radio emissions have been found to correlate with hard X-ray emissions of energetic electrons presumably hitting the chromosphere. They constitute complementary information on electron beams, their acceleration and the medium in which they propagate.

Most interesting may be narrowband spikes of a few tens of millisecond duration. The low-frequency kind (200–500 MHz) is well correlated with metric signatures of electron beams (individual type III bursts). Its source has been found by VLA observations to be at high altitude in the corona. Both spectral and imaging observations of low-frequency spikes suggest that they occur near or within the acceleration region. Although the spike sources are generally believed to be smaller than about 100 km, recent VLBI observations have overresolved them at 2.2 GHz. Scattering in the corona may be the interpretation.

1. Introduction

Coherent emission is radiated by collective plasma processes and can thus reach a brightness temperature in excess of the kinetic temperature of the radiating particles. If such a radiation process occurs, its efficiency of turning particle energy into radio emission can highly exceed the efficiency of incoherent mechanisms, such as bremsstrahlung or gyro-synchrotron emission.

Coherent emissions are well known from metric solar bursts (e.g. review by Benz 1993). They are driven by velocity space anisotropies, like beams and trapped particles, or waves excited by various means. Radio waves are generally produced at one of the characteristic frequencies of the background plasma, most frequently at the plasma frequency, the electron gyrofrequency or their low harmonics.
For the plasma frequency and electron gyrofrequency to be in the decimeter range (defined here as 0.3 to 3 GHz) an electron density of $10^{8-11}$ cm$^{-3}$ and a magnetic field of $10^2-3$ G is required, respectively. These values are generally believed to be typical for the region of flare energy release.

Why have decimetric radio emissions only recently received attention? Metric radio bursts (Types I to V) were easier to observe and to understand, and thus were of primary interest in the 1950–1960's. Also, decimetric plasma emission was believed to be strongly absorbed (as predicted by isotropic, barometric models of the corona). On the other hand, gyro-synchrotron radiation peaks beyond 5 GHz and was known to be weak in the decimeter range.

Early observations of decimetric waves were made at single frequencies by many people including Kundu & Firor (1961), Takakura & Kai (1961), and Krishnan & Mullaly (1962). The first spectrometers built in the early 1960's at Fort Davis, Owens Vally and Culgoora gave a preliminary overview at relatively low spectral and temporal resolution. In the late 1960's the Dwingeloo spectrometer came into operation with high sensitivity and resolution in a narrow band.

Much effort of the early observers went into the analysis and interpretations of the spectacular outbursts (decimetric Type IV bursts) and their fine structures. It was realized only later (Kuijpers 1980 for a review) that the outbursts are produced by a few trapped particles radiating very efficiently. These emissions are most similar to the highly polarized radio flares of dMe and dKe stars.

Dröge (1967, 1977) was the first to observe time structures of a few tens of milliseconds at 0.46 and 1.4 GHz. Later Slottje (1978) found similar structures at 2.8 GHz and pointed out that they occurred in the impulsive phase of flares.

In recent years it has become increasingly clear that the primary flare energy is first released into energetic electrons to a considerable fraction (possibly 20% or more). The particle energies reach 100 MeV, and more for ions. Thus flares are efficient accelerators, and their nonthermal electrons are likely sources of coherent radio emission.

2. Surveys and Classification

Surveys of flare radio emissions became possible with the availability of broadband spectrometers having sufficient time and frequency resolution. Recently, surveys of coherent emissions, each extensively covering a limited fraction of the spectrum, have been published:

- 0.3–1.0 GHz (0.1 s / 3 MHz) Güdel & Benz (1988)
- 1.0–3.0 GHz (0.1 s / 12 MHz) Isliker & Benz (1994)
- 4.0–8.0 GHz (0.0005 s / 100 MHz) Allaart et al. (1990)
- 6.5–8.5 GHz (0.1 s / 10 MHz) Bruggmann et al. (1990)

The time/frequency resolution is indicated in parenthesis.

A useful classification should separate bursts that can probably not be explained by the same mechanism. It is somewhat dependent on resolution. Using
the surveys made from high spectral resolution observations with the Zurich instruments, five major types have been reported in the 0.3–8.5 GHz range:

1. Long-duration outbursts (decimetric type IV): \textit{trap-plasma instability}

2. Fast-drift bursts (type III): \textit{beam-plasma instability}

3. Pulsations: \textit{trap-plasma instability}

4. Narrowband spikes: \textit{trap-plasma instability, current instability} (?)

5. Patches of continuum: \textit{ion-beam instability} (?)

Tentatives drivers of the emission as proposed by various authors are indicated in italics. Note that the word “spike” is used in a restricted sense here and does not include any short duration peak.

The five types differ in bandwidth, duration, polarization, and drift in the frequency–time plane. There are few (\(\approx 10\%\)) overlap and borderline cases if observed with a spectro-polarimeter (Isliker & Benz 1994). Figure 1 suggests a simple scheme, in duration and bandwidth, how the five types are distributed. The boundaries are frequency dependent, in particular durations become shorter at higher frequency. The scheme should not be used blindly.

3. \textbf{Beam-Plasma Instabilities}

Propagating nonthermal electrons develop a beam-plasma instability if the forward gradient in velocity distribution becomes positive. Radiations of the beam instability have been known since the 1950’s, particularly in the metric range, under the name of type III radio bursts; for a review see Suzuki & Dulk (1985).
Figure 2.  Top: Radio flux density of solar type III emission observed by a spectrometer in Zurich and displayed in the form of a spectrogram (frequency vs. time, enhanced emission black). Two reversed slope bursts starting at 600 MHz mark two downgoing beams. The second one is accompanied by a simultaneous upgoing beam ($\nu < 550$ MHz). Bottom: HXR count rate measured by BATSE (Benz 1993).

The emission is at the fundamental or second harmonic of the plasma frequency as confirmed by interplanetary in situ measurements.

Occasional coincidences of single type III bursts with peaks in the solar hard X-ray (HXR) emission have been reported (e.g. Kane et al. 1982, Sawant et al. 1994). Recently, Aschwanden et al. (1995) find that 30% of all short HXR peaks are associated with a type III burst within one second. The time delay of the associated bursts has approximately a Gaussian distribution excluding significant random coincidences. Most of the associated bursts start in the decimeter range and drift in the frequency–time plane to lower frequency, suggesting a beam moving upward in the corona. On the other hand, HXR emission is usually interpreted by the thick target model of a downward moving beam hitting the chromosphere. Obviously, the two beams are not identical.

A close inspection of the associated type III bursts has revealed that 47% have reversed drift or same (often weak) reversed-drift extension to higher frequency. An exceptionally clear example of a bidirectional type III burst is shown in Fig. 2. It appears that the energetic electrons are injected or accelerated at a height corresponding to 600 MHz from where two beams propagate; one up, the other down the corona. The observed correlation of short HXR peaks with individual type III bursts thus is likely to be caused not by the same electrons, but by a common acceleration event.

Usually there are much more type III bursts in a flare than HXR peaks, and not every decimetric type III burst is associated with a HXR peak. Nevertheless,
Figure 3. Spectrogram of a group of metric type III bursts ($\nu < 326$ MHz) associated with metric spikes ($326 < \nu < 360$ MHz). Enhanced emission is bright. Observation of a radio spectrometer at ETH Zurich (Benz et al. 1995b).

every radio burst requires the acceleration of a new beam. Up to 1000 decimetric type III bursts have been recorded in a single flare, suggesting that electron acceleration is not continuous, but fragmented (Aschwanden et al. 1990).

4. Narrowband Spikes

Narrowband spikes have been reported from 0.3 to 8 GHz for more than 30 years. The low-frequency variety, called "metric spikes" for their occurrence in the 200–500 MHz range, has recently received some attention. Metric spikes (cf. example given in Fig. 3) are not associated with HXR emission, but occasionally with $H\alpha$ flares and always with metric type III bursts. Their circular polarization is higher than that of the type III bursts making them easy to be recognized in polarigrams. Benz et al. (1995a) find that 34% of the type III groups with starting frequency below 500 MHz are associated with spikes. The metric spikes always occur at higher frequency than the start frequency of normal-drifting type III bursts.

The relation between the metric spikes and the associated type III bursts has been investigated by cross-correlation. The frequency channel containing the highest spike activity (343 MHz in Fig. 3) has been selected as the reference. The cross-correlation was calculated as a function of the delay time, and the peak of the cross-correlation was determined for each frequency channel. Figure 4 shows
the result. The reference channel contains the autocorrelation, and its peak (full
circle) is therefore at zero delay.

The frequency axis of Fig. 4 is logarithmic, so that beams traversing a
barometric atmosphere at constant speed would appear as straight lines. The
regression line through the type III channels (230–326 MHz) misses the full circle
by $0.03 \pm 0.03$ s. Benz et al. (1995a) find that the average of this time difference
is compatible with zero. This result suggests that metric spikes are emitted (i)
at a frequency similar to type III bursts (fundamental or harmonic of the plasma
frequency) and (ii) within a few 1000 km of the path (or its origin) of the beam.

In the first image of metric spikes, Krucker et al. (1995) find that the
sources appear at three slightly different locations at very high altitude (350,000
to 450,000 km above the photosphere). This may explain why no associated
HXR and microwave emission has yet been found.

Krucker et al. (1995) also note a thermal source at higher frequency and
lower altitude that peaks about 40 seconds after the metric spikes. It may be
interpreted by an energy release of $0.8 - 8 \times 10^{29}$ erg near or in the spike region.
Hot plasma has been suggested to expand up and down along a nearly vertical
field line, heating the lower corona by the bulk of the electrons and exciting a
type III burst by the fastest upgoing particles.

In the best cases, the number of metric spikes per type III burst is 5–10.
As the duration of a single spike exceeds 100 ms (the instrumental resolution in
observations like Fig. 3), the spikes are often superimposed. Higher resolution
data may increase the number.
The interpretation of the spike emission process is still open. Maser models requiring a loss-cone distribution of magnetically reflected electrons have been developed for the decimetric variety, but seem to be difficult to apply to the type III associated metric spikes. Variants of the beam-plasma instability have been proposed by Zheleznyakov & Zaitsev (1975), Chernov (1977), Kuijpers et al. (1981) and Wentzel (1993). Another possibility is that the spike source is located in the energy release and/or acceleration region, where the unstable current drives low-frequency turbulence which may coalesce with Langmuir waves into radio emission (Benz 1986, Kliem 1995).

Recent interferometric observations report surprisingly large spike sources: the VLA measurement of the diameter of metric spikes (330 MHz) yields 68'' (Krucker et al. 1995) and VLBI of decimetric spikes at 2.3 GHz (Benz et al. 1995b) measured a lower limit of 0.1''. Both results can, however, be interpreted as the result of scattering in the corona (Bastian 1994) of a much smaller source. Less than about 100 km is required from arguments based on the small bandwidth (Benz 1986).

5. Conclusions

The dominant coherent decimetric radio emissions during the impulsive phase of solar flares are beam-plasma instabilities (type III bursts) and narrowband spikes. Both emissions are more structured in time than any other flare radiation. In the case of decimetric type III it has become increasingly clear that the multitude of radio structures reflect a fragmented acceleration of electrons. This is possibly the result of current filamentation and a fragmentation of the flare energy release process.

It is still not clear whether narrowband spikes reflect an even more fragmented structure of the flare process. The metric spikes have now been definitively related to the acceleration or propagation of beams. They occur at high altitude and very likely in or near the acceleration region.

In the future, more imaging data on decimetric radio emissions is urgently needed. Combined with spectral information they yield essential information on formation of beams and plasma waves in the flaring region. The decimetric radiations are complementary to X-ray and microwave emissions. They are coherent, thus can be very efficient, but are more difficult to interpret quantitatively as they depend on the velocity distribution of the non-thermal particles as well as the ambient plasma parameters. Some of the sources may be close or within the acceleration site and give direct information on primary processes. Finally, it seems very promising to relate the presently available soft X-ray images of the thermal background plasma to the non-thermal phenomena apparent in decimetric emissions.

References

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