RADIO EMISSION OF SOLAR FLARE PARTICLE ACCELERATION

A. O. Benz*

Abstract

The solar corona is a very dynamic plasma on time scales of decades to a few milliseconds. Radio missions provide diagnostic tools particularly suited for the analysis of non-thermal electron distributions, enhanced levels of various kinds of plasma waves and plasma phenomena related to electron acceleration in flares. Very intense coherent emissions are observed at frequencies below about 3 GHz, weaker ones up to 9 GHz. They are caused by plasma instabilities driving various wave modes that in turn may emit observable radio waves. The focus here is on Type III and stationary type IV bursts from about 0.2 to 4 GHz. Type III bursts can be traced back in the corona to the acceleration region of electron beams. Less known are radio emissions from magnetically trapped electrons driving loss-cone unstable waves. This is the interpretation usually given to type IV emission. It is a very powerful radiation probably also observed in stars and possibly related to acceleration after the main flare energy release phase. The comparison of the radio emissions with hard X–rays reveals surprisingly that the two emissions often do not correlate in time and thus must originate from different electron acceleration processes. In combination with other wavelengths and their recent imaging capabilities, exciting new possibilities may soon open for radio diagnostics.

1 Introduction

The study of the solar corona over the past fifty years has posed more new questions than answered old ones. An important result is that non-thermal particles play a major role in the long-standing enigma of coronal flares. Radio emissions have provided important tools. Contrary to planetary plasmas, the solar corona includes dense plasma, with a plasma frequency, ω_p, usually much larger than the electron gyrofrequency, Ω_e. Some of the solar radio emissions are related to flares, processes that release up to 10^{32} erg with a major energy fraction residing initially in non-thermal electrons [Emslie et al. 2004; Saint-Hilaire and Benz 2005]. Their energy is distributed according to a power-law in energy, starting at $\gtrsim 10$ keV. The process also accelerates ions at the same time but with

* *Institute of Astronomy, ETH Zürich, 8092-Zurich, Switzerland*

less known efficiency. Thus acceleration is not one of many things that happen during flares, but an essential part of the primary energy release, and the main flare process may be considered as a particle accelerator.

The free mobility of charged particles in a dilute plasma and the difference in inertia between electrons and ions make it likely that electrons are accelerated in every major impulsive process. Free magnetic energy that can be converted into other forms of energy requires the presence of an electric current and an associated electric field before the flare-like process. Waves of various types from MHD to collisionless are expected to be excited by the flare and are also capable to accelerate particles in resonance. From a plasma physics point of view, acceleration is not surprising; controversial is, however, which process dominates.

The conversion of magnetic energy into accelerated particles can be accomplished by several processes. It is likely that more than one occurs during a flare and its secondary effects. The most widely discussed can be grouped into 3 types [e.g. Melrose 1990]:

- electric field parallel to the magnetic field,
- stochastic acceleration (e.g. resonant acceleration by waves), and
- perpendicular and parallel shocks (first and second order Fermi acceleration).

A very popular acceleration model for solar flares is stochastic acceleration by low-frequency waves [Miller et al. 1997, Schlickeiser 2002]. The waves assumed in this model are unlikely to couple into radio waves. Other models, in particular those based on electron beams producing waves to accelerate ions [Miller & Vinas 1993; Roth & Temerin 1997], are prone to predict intense radio emission. Whether coherent radio emission is emitted or not, is therefore an observable criterion for the validity of acceleration models. The various emissions are briefly introduced. The focus of this review then is on some radio emissions that are most promising in yielding information on electron acceleration in flares with emphasis on recent results from our group.

2 Flare Emissions at Decimeter Wavelengths

For a long time, decimetric emissions were the least studied radio phenomena of solar flares. Situated in the spectrum between the metric range ($\lesssim$ 300 MHz, well-known for its five types of bursts) and the centimetric (or microwave) synchrotron emissions at frequencies $\gtrsim$ 3000 MHz, the decimetric emissions manifest a large variety of structures, many of which are still little explored. An example of an event rich in various emissions is shown in Figure 1. Note that emissions marked as 'metric' appear distinct from the bursts generally found at higher frequency. The event starts with a group of metric type III bursts at 200 – 400 MHz. Later and about simultaneously, metric type V activity, type III bursts in the range 350 – 750 MHz, decimetric pulsations and gyro-synchrotron emissions start. The type III bursts at 09:34:20 and 09:36:20 UT are termed 'metric' because they appear to be very similar to metric type III bursts, shifted to higher frequencies in this case.

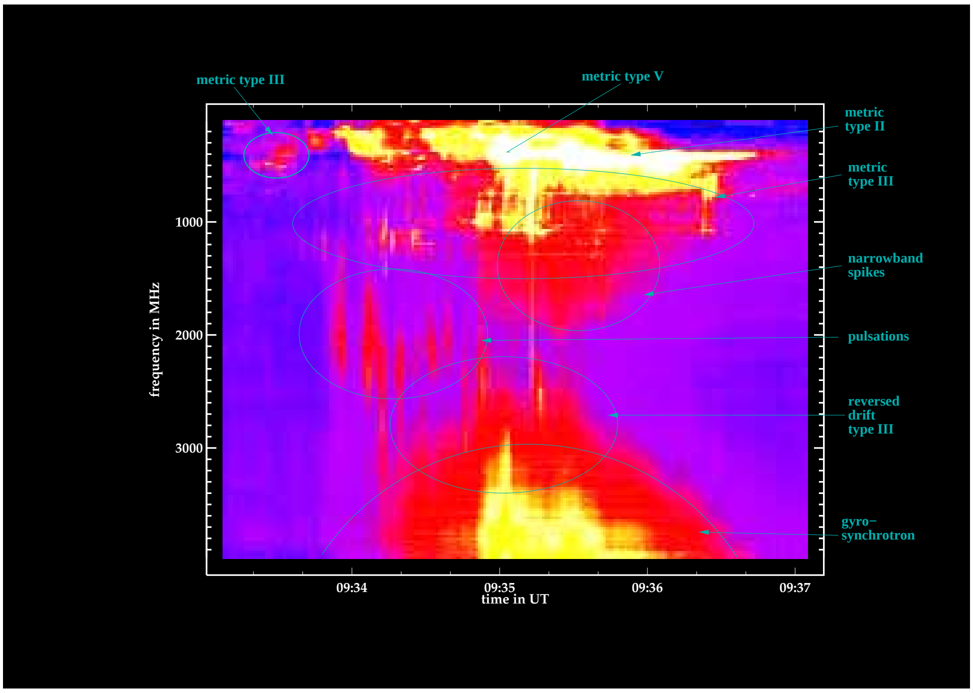

Figure 1: Broadband spectrogram recorded with the Phoenix–2 spectrometer of ETH Zurich on 2001/12/10 showing a rich event in meter and decimeter wavelengths. Enhanced radio flux density is indicated bright. The solar background is subtracted. Various types of emissions are identified and discussed in the text (from [Benz, 2004]).

They drift upward in the corona (negative drift rate in MHz/s). The type III bursts at even higher frequencies, extending up to 3400 MHz in Fig. 1, have predominantly positive drift rate if measurable at all. An extremely broadband type III burst about in the middle of the figure is bidirectional, drifting up above 1400 MHz and down below. The fact that this frequency corresponds to the center frequency of the pulsations is interesting and deserves further investigation. The emission marked as narrowband spikes consists in fact mostly of a continuum with some interspersed spikes. Durations of the smallest structures in decimetric burst types generally decrease with increasing frequency.

As long as there is no definite way to relate burst types to emission processes, any classification into types and subtypes remains preliminary. Nevertheless, the decimetric bursts may be ordered by similarity of their shape in the dynamic spectra. The first such extended surveys and classifications were made by Güdel & Benz [0.3 – 1.0 GHz, 1988], Isliker & Benz [1.0 – 3.0 GHz, 1994], Bruggmann et al. [6.5 – 8.5 GHz, 1990]. The usual criteria taken into account were: bandwidth, duration, drift rate, substructures, impulsiveness, and order. The occurrence rate of the 0.8 – 2.0 GHz radio bursts and fine structures has been studied statistically by Jiricka et al. [2001]. Well over 90% of the events can be assigned to 6 classes:

1. *Decimetric type III bursts* (also termed "fast drift bursts"): Decimetric bursts shaped similar to metric and interplanetary type IIIs have short duration (about $0.5 - 1.0$ s) and high drift rates (usually < -100 MHz/s). They occur often in

groups of some tens to hundreds. Reverse drifts are as common as normal drift bursts. type III bursts are generally interpreted by electron beams interacting with the ambient coronal plasma to excite a bump-on-tail instability of Langmuir waves [Ginzburg & Zhelezniakov 1958]. The emission is produced at the local plasma frequency or, more likely at decimeter wavelengths, at its harmonic.

2. *Diffuse continua* occur more frequently in the 1–3 GHz range than in other ranges and have various forms. Their characteristic duration is between one and some tens of seconds, too long for a type III burst and too short for a type IV burst. The circular polarization is usually weak. Continua have been interpreted in terms of continuous injection of electrons [Bruggmann et al. 1990].

3. *Stationary type IV* events are continua of > 10 minutes duration occurring in the 0.1–3 GHz range. The emission is usually modulated in time on scales of 10 s or less, and is strongly polarized. It has been interpreted by electrons trapped in loop–shaped magnetic fields [Stepanov 1974; Kuijpers 1975].

4. *Pulsations* are frequent broadband emissions (several 100 MHz) with periodic or irregular short pulses. The quasi-periodic pulses have typical separations of 0.1 to 1 second, occur in groups of some tens to hundreds and last some seconds to minutes. The drift rates of individual structures exceed those of type III bursts by a factor of 3 [Aschwanden & Benz 1986].

5. *Spikes* of narrowband emissions appear in groups of up to ten thousand [reviewed in Benz 1985]. Individual spikes are very short (< 0.1 sec) and extremely narrowband (some MHz) intense emissions. Clusters of spikes are sometimes organized in small subgroups or chains. Metric spikes are observed at altitudes below metric type III sources. In some cases, harmonic structure is present. Very few cases below 300 MHz have been reported.

6. *High-frequency continua* are apparently featureless, broadband emissions above about 1 GHz. They are generally attributed to the gyro-synchrotron mechanism of mildly relativistic electrons. The emission continues often into the centimeter, millimeter, and sometimes even sub-millimeter bands [Kaufmann et al. 2002].

The small instantaneous bandwidths of the first 5 classes suggest a coherent emission process. Coherent means here that the emission is not radiated by individual particles, but in joint action (i.e. phase coherent), organized by a wave in the plasma. They have been noted up to 8.5 GHz [Bruggmann et al. 1990]. If coherent emission is emitted at twice the plasma frequency, the wavelength range of one meter (300 MHz) to 4 cm (8 GHz) corresponds to a range of densities of 3×10^8 to 2×10^{11} cm^{-3}. The plasma frequency is defined by

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} = 2\pi\ 90\sqrt{\frac{n_e}{10^8 cm^{-3}}} \quad [MHz], \tag{1}$$

where e is the elementary charge, m_e the electron mass and n_e the electron density. The range of densities corresponds to the values expected for the primary flare energy release and acceleration sites. More speculative are emissions produced directly by the acceleration process, involving e.g. instabilities of electric currents [Benz & Wentzel 1981; Kuijpers, van der Post, & Slottje 1981].

High-frequency waves couple into radio waves. This is considered the standard emission process in the solar atmosphere, where $\Omega_e \ll \omega_p$. Wave-wave coupling, also termed *wave coalescence*, requires

$$\omega_1 + \omega_2 = \omega_3 \quad (2)$$

$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 \quad (3)$$

This system of equations, referred to as the parametric equations, expresses the conditions for effective transfer of wave energy between wave 1 (ω_1 and $\mathbf{k}_1$) plus wave 2 into a third wave that may be the electromagnetic wave observed as radio emission. Wave coalescence is a well confirmed process, corroborated by *in situ* observations in the interplanetary medium, where wave 1 was identified as a Langmuir wave and wave 2 either an ion acoustic wave (fundamental plasma radiation) or an oppositely directed second Langmuir wave (harmonic) [Lin et al. 1986; Cairns & Robinson 1995].

Using radio emission as a diagnostic of acceleration and energy release processes or to derive the plasma parameters of these regions requires some interpretation of the coronal radio emissions. In most cases, except for type III bursts, the interpretation is still disputed. The combination of observations in other wavelengths, in particular X-ray and EUV emission helps to constrain the many possible radiation mechanisms and to interpret some further observations. In the following, examples of recent progress in the interpretation of dynamic plasma processes of the corona due to radio diagnostics are presented. These are necessary steps to understand the release of magnetic energy in the corona, the acceleration of particles and the heating to several million degrees.

3 Electron Beams and Acceleration Sites

Bursts that rapidly drift in frequency as time progresses (type III) are generally interpreted as the signature of electron beams propagating through the corona and interplanetary medium. type III bursts trace the path of the beam from near the acceleration site toward the final destination of the electrons as long as the beam is capable to excite radio emission. As the beam excites plasma waves at the local plasma frequency, the frequency changes with density according to Eq. (1). type III bursts are currently the most useful and important coherent bursts since their physics is at least qualitatively understood. The recent interest in type III bursts is motivated by their use as diagnostics for the location of the electron acceleration process, as tracers of the magnetic field lines along which electrons propagate, and the density of the ambient corona they traverse.

Direct information on the acceleration process may possibly be obtained from narrowband metric spikes. They are found in 10% of all meterwave type III groups near but slightly above the start frequency of the type III bursts [Benz et al., 1982]. Small clusters of metric spikes correlate in time with individual type III bursts (Fig. 2) thus with the acceleration

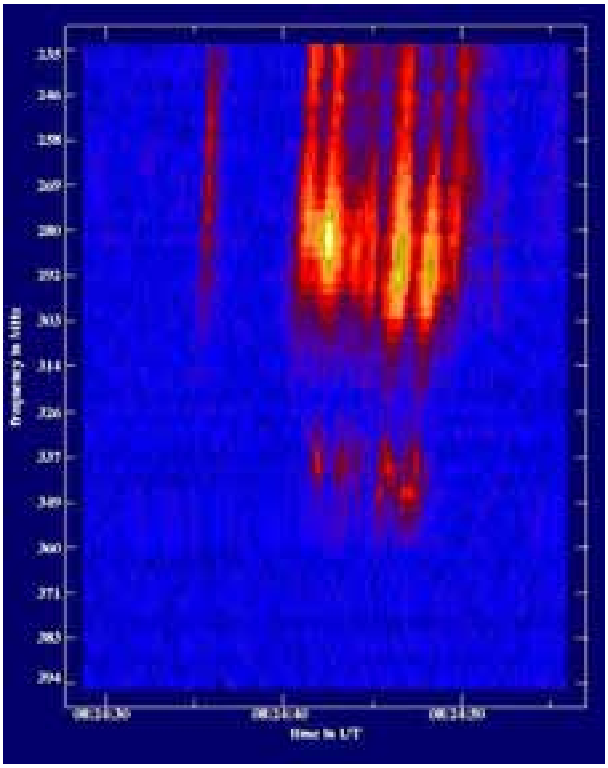

Figure 2: Dynamic spectrogram of 230 – 400 MHz total flux observed the Phoenix-2 radio spectrometer. Enhanced emission is shown bright. In the upper part of the image, type III bursts are seen, drifting rapidly to lower frequencies. In the lower half, short duration metric spikes are visible.

of electron beams. The spikes are concentrated in the spectrogram on the extrapolation of the type III bursts to higher frequency. Furthermore, Fig. 3 suggests that metric spikes are located on the extension of type III trajectories, supporting a model of energy release in or close to the spike sources. If this is the case, radio observations can locate the energy release and measure the electron density.

Metric spikes have been found to be associated in some cases with impulsive electron events in the interplanetary medium [Benz et al., 2001]. The low energy cut off of the interplanetary electron distribution defines an upper limit of the density in the acceleration region. The derived electron density is of the order of 3×10^9 cm^{-3}, consistent with the density in the source of metric spikes, assuming second harmonic plasma emission.

Imaging observations have shown that type III sources are often not single, but emerge simultaneously into different directions. Klein et al. [1997] have reported that down-propagating branches of type III bursts are sometimes double sources. Their simultaneous existence suggests a common origin. Paesold et al. [2001] have found double type III sources to diverge from the same spike source (Fig. 3). These findings support the hypothesis that narrowband metric spikes are closely related to the acceleration region. The multiplicity of the beam paths, on the other hand, is consistent with the predictions of the reconnection scenario for magnetic energy release where magnetic field lines from different directions meet closely.

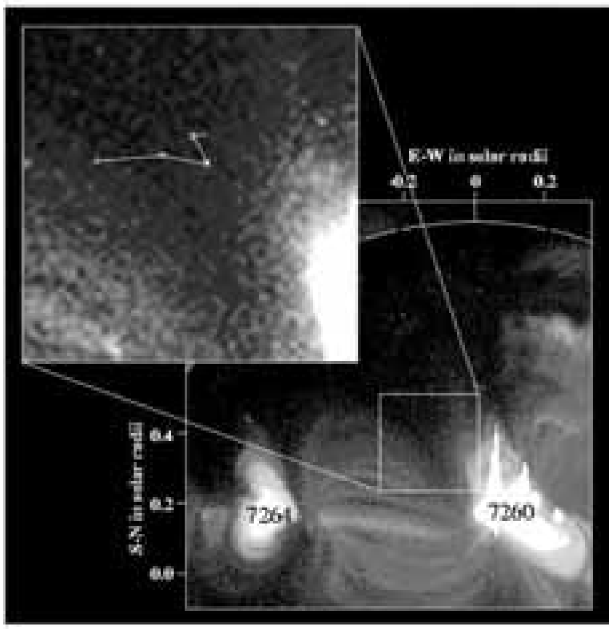

Figure 3: Insert: type III and metric spike sources overlaid on a Yohkoh/SXT image. The centroid positions of the sources at different frequencies at peak flux (observed with the Nançay Radioheliograph) are connected by lines. Two curves originate from the same location at the highest frequency, where the ETH Zurich radio spectrometer has observed metric spikes (from [Paesold et al., 2001]).

It must be noted here that there is no quantitative theory yet of coronal type III bursts. type III bursts appear under such different conditions than in interplanetary space that accepted theories may not simply be applied to coronal counterparts. Many parameters influence the emissivity, such as beam formation, magnetic defocusing, plasma beta, re-absorption by beam electrons, free-free absorption, scattering etc. The major unknown in the problem, however, is the evolution of the "bump-on-tail" instability. Some argue that it will develop until saturation by plateau formation or by Langmuir soliton formation. Others have presented evidence that wave growth is quenched by density inhomogeneity of the background plasma, shifting the frequencies out of resonance with the beam. The latter process has been modeled by the Stochastic Growth Theory [SGT, Robinson, Cairns & Gurnett 1992]. It assumes that the Langmuir waves grow exponentially until the beam and resonant waves meet some stochastic change in ambient density. A major advantage of the theory is its quantitative modeling of the emission process and its predictive power. It allows in principle to deduce the number of beam particles involved in the emission. The SGT has been successfully applied to interplanetary type III bursts [Robinson & Cairns 1994] and radio emission at the bow shock of the Earth [Kuncic et al. 2002, 2004]. More recently, some evidence for SGT has also been presented for coronal type III bursts. The observed peak flux of type III bursts was found to increase with drift rate and its distribution is a power-law, in agreement with theoretical predictions [Benz, Hirt & Trachsel 2005b].

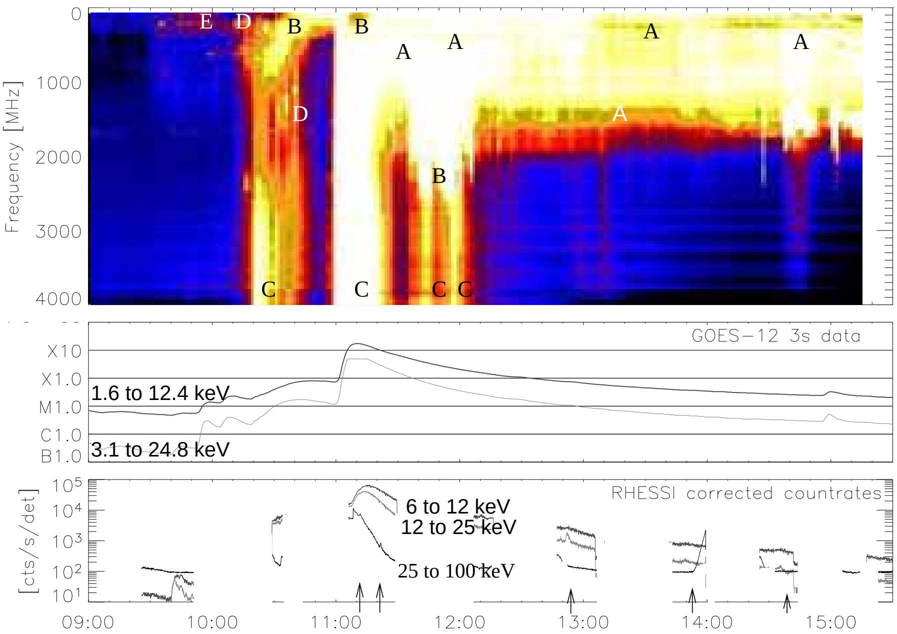

Figure 4: Observations of the X17 flare on 2003, October 28, in radio waves (top), soft X-rays (middle), and hard X-rays (bottom). The various radio emissions have been identified in enlargements and are marked by A for 'after main flare energy release phase', B for slowly drifting structures, C for high-frequency continuum (gyro-synchrotron emission), D for type III bursts, and E for noise storm (type I bursts). Subpeaks in hard X-rays are indicated by S (from [Benz et al., 2005a]).

4 Late-phase Emissions

Large solar flares have long been known for intense radio emissions at decimeter wavelengths after the main phase of energy release. As an example, Fig. 4 displays the observations of an extremely large flare (GOES class X17.2). It consists of an M9 preflare (at 10:30 UT) followed by the main peak occurring in the same active region. RHESSI missed the first peak and started to observe at the main hard X-ray peak. Both peaks were associated with strong gyro-synchrotron emission extending from the instrumental limit at 4 GHz down to about 1 GHz. At the low-frequency limit of the spectrogram, shock signatures (type II bursts) are associated with both main flare peaks at 10:32 and 11:10 UT ($\lesssim$ 500 MHz). A decimetric drifting ridge can be identified in higher resolution than shown in Fig. 4 at 11:48 UT and 2000 MHz. After the main phase of the flare, starting around 11:20, a bursty continuum extending from meter waves up to 1000 MHz appears, classified as stationary type IV event. It is intermingled with bright, narrowband emissions (marked "A" in Fig. 4) that pulsate and reach up to 4000 MHz. The type IV emission has been observed to spread in size with the speed of the Moreton wave until the radio emission reaches the lateral extent of the associated coronal mass ejection [Pick et al. 2005].

Hard X-rays (> 12 keV) are observed during most of the time of enhanced radio emission. The most intense radio emissions are not due to electron beams. Some are late–phase emissions apparently not directly related to the primary energy release and acceleration process. These radio emissions, generally classified as type IV and DCIM bursts, have previously been interpreted by loss–cone emission of trapped electrons. However, radio and hard X–ray subpeaks do not show a detailed correlation, and long–term trapping can be excluded. Hard X–ray subpeaks are found in 27% of the radio subpeaks covered by RHESSI. Total duration, peak flux, and radiated energy of the radio emissions correlate with the flare energy released (measured in soft X–rays).

An interpretation of extended radio emissions with shocks does not fit the standard radio shock signatures represented by narrowband structures drifting slowly in the spectrogram (type II radio bursts and decimeter drifting ridges). Such structures in the 2003, October 28 flare, marked B in Fig. 4, occurred only early in the late–phase of the flare. Therefore, type IV radio emission does not appear to be directly associated with CMEs, traveling already far from the radio sources at those times. Secondary acceleration at the time of the radio emission remains the most likely interpretation of type IV and decimetric pulsation emissions. Such acceleration may be the result of the reconfiguration of the active region magnetic field after a large flare. This interpretation suggests that the corresponding hard X–ray subpeaks may often be buried in other emissions so that they are not observable. It is supported by the association of type IV emission with interplanetary electrons [Klein et al., 2005]. The lack of close temporal correlation between radio emission and hard X–rays also implies enhanced radio emissivity per accelerated electron in energy releases after the main flare.

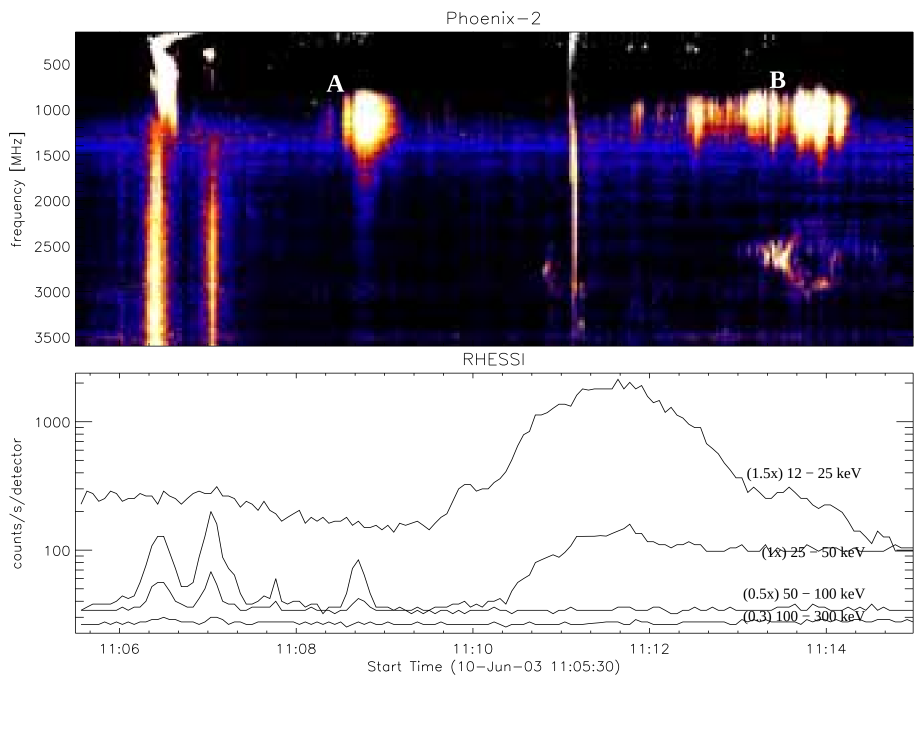

Figure 5: Radio emission of flares as observed by Phoenix-2 (top) and hard X-rays observed by RHESSI (bottom). Radio and X-ray emissions at 11:06-07 and 11:11 UT correlate with high-frequency continuum, type III bursts and spikes (A), but late-phase emission in the form of decimeter pulsations at 11:12–14 UT, 700 – 1500 MHz does not correlate (from [Benz et al. 2005c]).

5 Relation to Hard X–rays

Radio radiations observed during major energy release (as observed in hard X–rays) may be candidates for direct emission by the accelerator. X–ray bremsstrahlung emitted by electrons is a quantitative tracer for energy release. Radio and X–ray observations may be compared both in time and spatial location, but the latter has been studied only for individual events. The temporal relation may be simultaneous emission (association) or a parallel temporal evolution in detail (correlation).

Temporal associations have been first made for type III bursts. Only 3% of meter wave type III bursts are associated with impulsive HXR emission [Kane 1981]. However the association increases with increasing type III start frequency and with intensity. Since metric type III bursts originate high above active regions and propagate mostly upwards, it is perhaps not surprising that they are poorly associated with HXR events. Aschwanden et al. [1985] show that 48% of reverse-drift type III bursts at decimeter wavelengths are associated with HXR bursts, consistent with the expectation that downward-directed electron beams should correlate better with thick target HXR emission than upward-directed beams. However, not every HXR peak is associated with a radio burst. Most surprising is the large range of observed ratios between associated radio emission and X-ray flux. The range exceeds 9 orders of magnitude from intense groups of meter wave type III bursts without X-ray counterpart to large HXR events without coherent radio emission at meter and decimeter waves [Benz et al 2005c].

Out of 201 HXR flares, 153 were associated with decimetric pulsations. Figure 5 shows examples together with gyro–synchrotron emission visible at high frequencies above about 3 GHz and reported up to 15 GHz in Solar Geophysical Data. The decimetric pulsations at 11:12–14 UT in Fig. 5 have a non-thermal spectrum that is too narrow for gyro-synchrotron emission. Thus a coherent process is probably the source. Recently, some pulsations in decimeter waves have been found that correlate with hard X–ray emission [Kliem et al. 2000, Saint–Hilaire & Benz 2003] or to be directly associated with soft X–ray ejecta [Khan et al. 2002, Karlicky, Farnik & Meszarosova 2002].

Considering that flares generally accelerate non–thermal electrons prone to emit radio waves, one may expect that all flares are accompanied by coherent emissions. The reality is different and more complex: *(i)* Some 17% of large flares do not show radio emission in meter and decimeter wavelengths [Benz et al. 2005c]. *(ii)* X–ray associated radio emission appears in many different spectral forms varying enormously in bandwidth, polarization, fluctuation, duration and frequency drift. The origin of these widely different emissions does not appear to be identical, and several emission mechanisms seem to be at work. It is thus not immediately clear which emission originates from the main acceleration region, is due to escaping or trapped electrons, or is produced by some secondary shocks.

6 Conclusions

In the past, radio observations of solar flares have revolutionized our understanding of dynamic processes in the corona, giving first evidence for non-thermal particles, relativistic electrons, shock waves etc. The field of solar radio emission is extremely rich and still poorly fathomed. Here some recent results are selected to exemplify the current state.

Flares physics largely relies on secondary phenomena to infer on the processes of energy release and acceleration. Excellent examples are electron beams emitting radio waves (type III bursts) from centimetric to decametric radio waves. type III bursts have been used to locate the energy release site of small flares in the high corona. The altitudes are found higher than the locations determined typically from X–ray emissions suggesting different acceleration regions.

Coherent radio emissions in the short wavelength meter radiation may be emitted directly by the acceleration region. Firm evidence, however, is still missing. Metric spikes are the most likely candidates, but associated only with small energy releases. Although there are emissions of decimeter waves during the main hard X-ray phase of major flares, their origin is unclear. Pulsations are more abundant than spikes. Very little is known about their emission processes. Even if the identification of direct emission by the accelerator is not yet achieved, some conclusions on the acceleration physics may nevertheless be inferred. In particular, proposed acceleration processes can be tested on their general predictions for radio emission. Mechanisms that necessarily produce intense coherent radio emission in all events can be excluded. An example is electron acceleration in the form of beams. Such beams are unstable and would produce intense coherent radio emission in all cases, which is not observed. More direct inferences may become possible when the emission mechanisms of narrowband spikes and decimetric pulsations will be known.

With the advent of imaging observations in X–rays and EUV lines, outlining the context of the thermal coronal plasma, imaging observations of coherent radio emissions have become important. The location of the source relative to coronal loops allows to test the predictions of emission models. Thus it will become possible to distinguish between emissions by trapped electrons from radiations originating near or at the acceleration site. Still missing is a dedicated instrument at frequencies in the 0.5 to 3 GHz range with arcsecond accuracy in position. The planned Frequency–Agile Solar Radiotelescope (FASR), combined with existing EUV and X–rays instruments in space are promising ingredients for a new era of research in coherent radio emissions of solar flares.

References

Aschwanden, M. J., H. J. Wiehl, A. O. Benz, and S. R. Kane, Correlation of solar decimetric radio bursts with X-ray flares, *Solar Phys.* **97**, 159-172, 1985.

Aschwanden, M. J. and A. O. Benz, The frequency-time drift of pulsations, *Astron. Astrophys.*, **158**, 102-112, 1986.

Benz, A. O., M. Jaeggi, and P. Zlobec, Fine structure near the starting frequency of solar type III radio bursts, *Astron. Astrophys.*, **109**, 305-313, 1982.

Benz, A. O., Radio spikes and the fragmentation of flare energy release, *Solar Phys.*, **96,** 357, 1985.

Benz, A. O., R. P. Lin, O. A. Sheiner, S. Krucker, and J. Fainberg, The source regions of impulsive solar electron events, *Solar Phys.*, **203**, 131-144, 2001.

Benz, A. O., Decimeter burst emission and particle acceleration, in: The Solar Corona, Dordrecht: Kluwer Academic Press, 203–221, 2004.

Benz, A. O., and D. G. Wentzel, Coronal evolution and solar type I radio bursts — an ion-acoustic wave model, *Astron. Astrophys.*, **94**, 100-108, 1981.

Benz, A. O., H. Perret, P. Saint-Hilaire, and P. A. Zlobec, Extended Decimeter Radio Emission After Large Solar Flares, *Adv. Space Res.*, in press, 2005a.

Benz, A. O., S. Hirt, and O. Trachsel, Radio emission of electron beams in the solar corona, *Astron. Astrophys.*, submittet 2005b.

Benz, A. O., P. C. Grigis, A. Csillaghy, and P. Saint-Hilaire, Survey on Solar X-ray Flares and Associated Coherent Radio Emissions, *Solar Phys.*, **226**, 121-142, 2005c.

Bruggmann, G., A. Magun, A. O. Benz, and W. Stehling, Solar flare microwave observations with high spectral resolution, *Astron. Astrophys.*, **240**, 506-510, 1990.

Cairns, I. H. and P. A. Robinson, Ion Acoustic Wave Frequencies and Onset Times during type III Solar Radio Bursts, *Astrophys. J.*, **453**, 959-972 , 1995.

Emslie, A. G., H. Kucharek, B. R. Dennis, N. Gopalswamy, G. D. Holman, G. H. Share, A. Vourlidas, T. G. Forbes, P. T. Gallagher, G. M. Mason, T. R. Metcalf, R. A. Mewaldt, R. J. Murphy, R. A. Schwartz, T. H. Zurbuchen, Energy partition in two solar flare/CME events, *JGR*, **109 (A10)**, Issue A10, 10104ff., doi: 10.1029/2004JA010571, 2004.

Ginzburg, V. L., and Zhelezniakov, V. V., On the possible mechanisms of sporadic solar radio emission (radiation in an isotropic plasma), *Soviet Astronomy AJ.*, **2**, 653-678, 1958.

Güdel, M. and A. O. Benz, A catalogue of decimetric solar flare radio emission, *Astron. Astrophys.*, **75**, 243–259, 1988.

Isliker, H., and A. O. Benz, Catalogue of 1–3 GHz Solar flare radio emission, *Astron. Astrophys. Suppl. Ser.,* **104,** 145-160, 1994.

Jiricka, K., M. Karlicky, H. Meszarosova, V. Snizek, Global statistics of 0.8-2.0 GHz radio bursts and fine structures observed during 1992-2000 by the Ondrejov radiospectrograph, *Astron. Astrophys.*, **375**, 243-250 , 2001.

Khan, J. I., N. Vilmer, P. Saint-Hilaire, and A.O. Benz, The solar coronal origin of a slowly drifting decimetric-metric pulsation structure, *Astron. Astrophys.*, **388**, 363-372, 2002.

Kane, S. R., Energetic electrons, type III radio bursts, and impulsive solar flare X-rays, *Astrophys. J.*, **247**, 1113-1121, 1981.

Kaufmann, P., J.-P. Raulin, A. M. Melo, E. Correia, J. E. R. Costa, C. G. Giménez de Castro, A. V. R. Silva, M. Yoshimori, H. S. Hudson, W. Q. Gan, D. E. Gary, P. T.

Gallagher, H. Levato, A. Marun, M. Rovira, Solar Submillimeter and Gamma-Ray Burst Emission, *Astrophys. J.*, **574**, 1059-1065, 2002.

Karlicky, M., F. Farník, and H. Meszarosova, High-frequency slowly drifting structures in solar flares, *Astron. Astrophys.*, **395**, 677-683, 2002.

Klein, K.-L., H. Aurass, I. Soru-Escaut, and B. Kalman, Electron acceleration sites in a large-scale coronal structure. *Astron. Astrophys.*, **320**, 612-619, 1997.

Klein, K.-L., S. Krucker, G. Trottet, and S. Hoang, Coronal phenomena at the release of solar energetic electron events, *Astron. Astrophys.*, **431**, 1047-1060, 2005.

Kliem, B., M. Karlicky, and A.O. Benz, Solar flare radio pulsations as a signature of dynamic magnetic reconnection, *Astron. Astrophys.*, **360**, 715-728, 2000.

Kuijpers, J., P. van der Post, and C. Slottje, Runaway acceleration in a radio flare, *Astron. Astrophys.*, **103**, 331-338, 1981.

Kuijpers, J., A unified explanation of solar type IV DM continua and Zebra patterns, *Astron. Astrophys.*, **40**, 405-410, 1975.

Kuncic, Z., I. H. Cairns, S. Knock, P. A. Robinson, A quantitative theory for terrestrial foreshock radio emissions, *Geophys. Res. Lett.*, **29**, 2-1, 2002.

Kuncic, Z., Cairns, I. H., Knock, S. A., A Quantitative model for terrestrial foreshock radio emissions: 1. Predicted properties, *J. Geophys. Res.*, **109 (A18)**, 2108ff., doi: 10.1029/2003JA010125, 2004.

Lin, R. P., W. K. Levedahl, W. Lotko, D. A. Gurnett,and F. L. Scarf, Evidence for nonlinear wave-wave interactions in solar type III radio bursts, *Astrophys. J.*, **308**, 954-965, 1986.

Melrose, D. B., Particle acceleration processes in the solar corona, *Austral. J. Phys.*, **43**, 703-752, 1990.

Miller, J. A. and A. F. Vinas, Ion acceleration and abundance enhancements by electron beam instabilities in impulsive solar flares, *Astrophys. J.*, **412**, 386-400, 1993.

Miller, J. A.,P. J. Cargill, A. G. Emslie, G. D. Holman, B. R. Dennis, T. N. LaRosa, R. M. Winglee, S. G. Benka, S. Tsuneta, Critical issues for understanding particle acceleration in impulsive solar flares, *J. Geophys. Res.*, **102**, 14631–14659, doi: 10.1029/97JA00976, 1997.

Paesold, G., A. O. Benz, K.-L. Klein, and N. Vilmer, Spatial analysis of solar type III events associated with narrow band spikes at metric wavelengths, *Astron. Astrophys.*, **371**, 333-342, 2001.

Pick, M., J.M. Malherbe, A. Kerdraon, D.J.F. Maia, On the disk Hα and radio observations of the 2003 October 28 flare and coronal mass ejection event, *Astrophys. J.*, **631**, L97-L100, 2005.

Robinson, P. A., I. H. Cairns, and D. A. Gurnett, Connection between ambient density fluctuations and clumpy Langmuir waves in type III radio sources, *Astrophys. J.*, **387**, L101-L104, 1992.

Robinson, P. A. and I. H. Cairns, Fundamental and harmonic radiation in type III solar radio bursts, *Solar Phys.* **154**, 335-360, 1994.

Roth, I. and M. Temerin, Enrichment of ^{3}He and Heavy Ions in Impulsive Solar Flares, *A*strophys. J., **4**77, 940-957, 1997.

Saint-Hilaire, P. and A.O. Benz, Hard X-rays, ejecta, and their associated decimetric radio emission in solar flares, *Solar Phys.*, **216**, 205-224, 2003.

Saint-Hilaire, P. and A. O. Benz, Thermal and non-thermal energies of solar flares, *Astron. Astrophys.*, **435**, 743-752, 2005.

Schlickeiser R., *Cosmic ray astrophysics*, Berlin: Springer, 2002.

Stepanov, A.V., A mechanism for generating type IV solar radio bursts, *Soviet Astronomy*, **17**, 781-795, 1975.