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Energetic (HXR/GR) Emission from Flares: Implication for Particle Acceleration and Transport

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Abstract

This paper reviews a selection of observations in hard X-rays (HXR) and gamma-rays (GR) that allow us to derive quantitative constraints on the energetic electrons and ions accelerated during solar flares. We shall focus on the results obtained for the relative energy contents in electrons and ions in strong gamma-ray line (GRL) events as well as on the chemical composition of accelerated ions. We shall discuss new estimates of the upper limit of the energy contained in ions for electron-dominated events and briefly summarize new results concerning the relationship found between centimetric-millimetric emitting electrons and HXR/GR bremsstrahlung emitting ones.

Key words: Sun: flares - Sun: hard X-rays - Sun: gamma rays - Sun: particle acceleration

1. Introduction

Energetic particles play a large role in the physics of solar flares since they carry a large fraction of the magnetic energy released. Hard X-ray (HXR) and gamma-ray (GR) observations are the most direct diagnostics of the energetic electrons (from $\geq$ 10 keV to a few 100 MeV) and ions (from $\geq$ 10 MeV/nuc to a few GeV/nuc) accelerated during flares. The temporal and spectral characteristics of HXR/GR bursts provide strong constraints on the acceleration/transport process(es) at work during flares. Reviews of the constraints derived from the different timescales in HXR and GR observations can be found in e.g. Chupp (1996), Trottet, Vilmer (1997), and Vilmer, Trottet (1997). In this paper, we shall first briefly overview the different components produced by energetic electrons and ions in flares. In section 3, we shall discuss the relative values of the energy contained in electrons and ions estimated from the observations of strong gamma-ray line (GRL) flares. Section 4 will present some results concerning the preferential acceleration of heavy ions in flares. New results from PHEBUS/GRANAT concerning the short duration high energy ($\geq$ 10 MeV) electron bremsstrahlung transient bursts observed in some flares ("electron-dominated" events) are summarized in section 5 showing that, as in the case of GRL flares, the upper limit of the ion energy content can still be comparable to that of the electrons even if no significant GRL line is detected. Radio observations represent complementary diagnostics of the energetic electrons which are produced during flares. The relationship between centimetric-millimetric emitting electrons and HXR/GR bremsstrahlung emitting ones is investigated in section 6 , using observations obtained in a wide energy spectral range with PHEBUS/GRANAT. The new constraints which will be provided by the future combination of microwave to meterwave radio and HXR/GR spectral and imaging observations will be finally discussed.

2. HXR/GR Production Mechanisms and Observations

Electromagnetic radiation above 100 keV is one of the last spectral domain where no spatially-resolved observations have been made. As in many other astrophysical objects, this high energy emission results from interactions of fast particles with an underlying ambient medium. It thus represents a direct diagnostic of the energetic particles which are accelerated in flares. Solar flare gamma-ray emission shows both lines and continuum resulting from the interaction of energetic electrons and ions and has been described in many theoretical studies (see e.g. Ramaty, Murphy 1987 for a review). The energetic electrons produce bremsstrahlung continuum emission by their braking on the Coulomb field of ambient ions. This continuum is dominant below 1 MeV and again from $\simeq$ 10 to 50 MeV. For a fraction of events, this component can extend up to a few hundreds of MeV (e.g. Akimov et al. 1991; Leikov et al. 1993; Kanbach et al. 1993) indicating the acceleration of ultra relativistic electrons.

The gamma ray line spectrum produced through interactions of ions in the 1 MeV/nuc to 100 MeV/nuc range results from the deexcitation of nuclei, from the capture of neutrons and from the annihilation of positrons. In this paper, we shall focus on the observations of nuclear deexcitation lines which are either narrow or broad depending on whether they result from the bombardment of ambient nuclei by accelerated protons and α particles or from the inverse reactions in which accelerated C or even heavier nuclei collide with ambient H or He. The strongest narrow deexcitation lines are found at 6.129 MeV from ^{16}O, 4.438 MeV from ^{12}C, 1.779 MeV from ^{28}Si, 1.634 MeV from ^{20}Ne, 1.369 MeV from ^{24}Mg and 0.847 MeV from ^{56}Fe. The broad lines merge into a quasi continuum dominating the bremsstrahlung emission in the $\simeq$ 1 - 8 MeV range. The broadening of these inverse reaction lines results from kinematic effects because the excited C, N, O, Si, Ne, Mg, Fe nuclei continue to move rapidly after their collisional excitation. All the components described above result in a complex spectrum such as the one shown in figure 1. If the spectrum of accelerated ions extends above a few hundred MeV/nuc, their interaction with the ambient medium leads to nuclear reactions in which secondary products such as pions or neutrons are produced. Pion production then leads to a broad-band continuum decay radiation at energies above 30 to 50 MeV (with a broad peak around 70 MeV from neutral pion decay radiation). The neutrons, if energetic enough, may escape from the Sun and be directly detected in the interplanetary space ($\geq$ 50 MeV neutrons) or at ground levels ($\geq$ 200 MeV) neutrons) (see e.g. Chupp 1988 for a review).

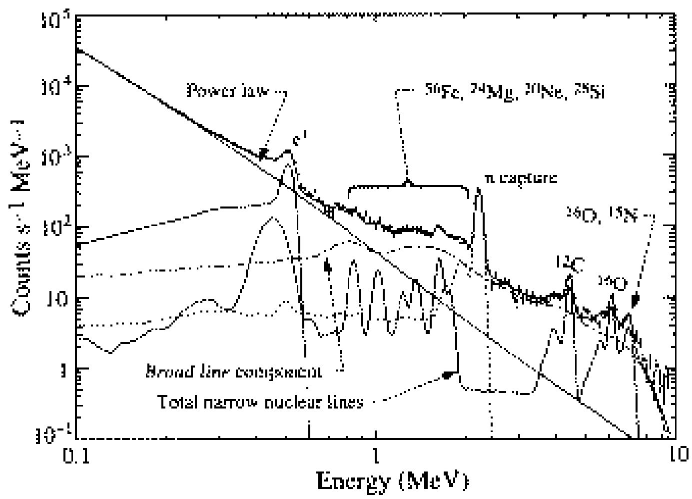

Fig. 1.. Count spectrum (accumulation time 2 minutes) observed by OSSE aboard GRO in the decay phase of the giant 4 June 1991 event (thick dark line) (from Murphy et al. 1997). The best fit decomposition of the spectrum into the different components is also shown: e.g. the power law continuum, the total narrow and the broad line components.

Since the first detection of solar gamma-ray lines by OSO-7 and Prognoz (Chupp et al. 1973; Talon et al. 1975), quasi-systematic observations have been obtained with spectrometers aboard SMM (see Chupp 1996 for a review and references therein) and Hinotori (Yoshimori 1989) for cycle 21, PHEBUS/SIGMA experiments aboard GRANAT (see e.g. Vilmer 1994; Trottet, Vilmer 1997), experiments aboard GRO/COMPTON (e.g. Murphy et al. 1994; 1997) and YOHKOH for cycle 22 (Yoshimori et al. 1994 and these proceedings). The analysis of these observations has led to a great deal of quantitative information for more than 20 GRL events (see e.g. Murphy et al. 1991; Share, Murphy 1995; Trottet et al. 1996; Ramaty et al. 1997) as well as to the observations of more than 40 events with significant emission above 10 MeV (see e.g. Rieger, Marschhäuser 1990; Vestrand et al. 1991; Pelaez et al. 1992; Vilmer et al. 1994: Rieger et al. 1998). The analysis of these observations have allowed to deduce many quantitative information on the accelerated electron and ion energy spectra, numbers and energy content as well as energetic ion chemical composition which provide useful constraints on the acceleration processes acting in the solar corona (see e.g. the review by Miller et al. 1997). Results on the energy contained in both electrons and ions as well as the abundances of accelerated ions will be discussed in this paper. Additional information (not discussed here) on the solar atmospheric elemental abundances can be deduced from the analysis of narrow gamma-ray lines (see e.g. Murphy et al. 1991; Share, Murphy 1995).

3. Electron and Ion Energy Contents in GRL flares

Different studies based on the quantitative analysis of several thousands of hard X-ray bursts above 20 or 25 keV (e.g. Crosby et al. 1993; Bromund et al. 1995) have shown that a major fraction of the released flare energy goes to accelerated electrons with an energy content ranging from $\simeq 10^{26}$ ergs for microflares (Lin et al 1984) to $\simeq 10^{34}$ ergs for the largest flares detected so far (Kane et al. 1995). Prior to the recent analysis of many GRL events leading to new estimates of the energy contained in ions, it was commonly believed that ion acceleration was secondary in the flare energy budget. It has now been shown that the energy contained in ions can be comparable to the energy in subrelativistic electrons. This results from the systematic analysis of 19 GRL flares observed by the GRS/SMM spectrometer by Share, Murphy 1995. The relative intensities of narrow gamma-ray lines (and in particular the ratio of the ^{20}Ne line at 1.634 MeV to the ^{16}O line at 6.129 MeV) measured in the different flares were further analysed by Ramaty et al. (1995; 1996). The measured ratios of the strong Ne line with respect to the O line imply that the accelerated ion spectra should extend as unbroken power laws down to at least about 1 MeV/nuc if a reasonable ambient Ne/O abundance ratio (i.e. in agreement with measurements of the Ne/O abundance ratio in the solar corona) is used. Ramaty et al. (1996) then estimated the energy contained in ions above 1 MeV/nuc assuming that: (i) the ion energy spectrum is an unbroken power law down to 1 MeV/nuc with a slope deduced from the ratio of the line fluences at 6.129 MeV and 1.634 MeV and assuming an ambient Ne/O of 0.25; (ii) the compositions of the medium and of the heavy accelerated particles are consistent with the results of other detailed studies of GRL spectra (i.e. coronal ambient composition and for the accelerated particles the composition is the same as that of impulsive solar energetic particle events in interplanetary space) (see e.g. Murphy et al. 1991). The derived ion energy contents for the 19 SMM GRL flares are shown in figure 2 and compared with the energy contained in ≥20 keV electrons for the same flares (Mandzhavidze, Ramaty 1996). In addition to these points, the energy contained in ions above 1 MeV/nuc (with α/p =0.1) are shown for two giant flares of June 1991 observed either by PHEBUS/GRANAT or OSSE (Ramaty et al. 1997; Murphy et al. 1997) . The ion energy content ranges from 4 10^{29} ergs to $\simeq$ 3 10^{32} ergs and may in some events exceed the energy contained in electrons above 20 keV. It thus appears that ions are equally as important as electrons in the flare energetics; this supports earlier suggestions (e.g. Simnett 1986) that ions may be energetically dominant in flares. The large fraction of the flare energy released in accelerated particles is thus roughly equipartitioned between electrons and ions with however a variation from flare to flare of the relative importance of both components (see also section 5).

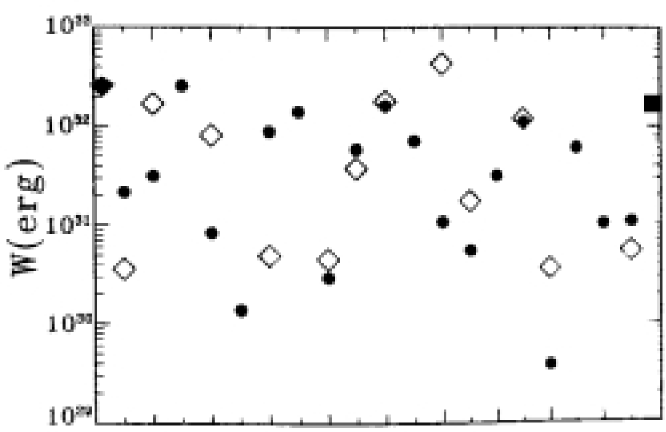

Fig. 2.. (adapted from Miller et al. 1997) Energy contained in ≥ 1 MeV/nuc ions (solid dots) for the 19 GRL flares observed by GRS/SMM (from Ramaty et al. 1995). The open diamonds indicate the energy contained in ≥ 20 keV electrons for 12 of these flares (from Mandzhavidze and Ramaty 1996). The solid diamond and the solid square represent respectively the energy contained in ≥ 1 MeV/nuc ions for the 1 and 4 June 1991 events (Ramaty et al. 1997; Murphy et al. 1997).

4. Acceleration of Heavy Ions in GRL Events

Even though most of the energy contained in ions resides in protons and α particles, crucial information on the efficiency of acceleration mechanisms based on resonance between particles and waves (see e.g. Miller et al. 1997 for a review) can be obtained from estimations of the abundances of accelerated ions. Such an estimation can be derived from gamma-ray spectroscopy of flares, but has been performed so far only for two events. The first study dealt with a complete determination of both the narrow and the broad components of a gamma-ray line spectrum observed by SMM (Murphy et al. 1990; 1991). It found that: (i) the ambient composition of the GRL producing region is consistent with coronal abundances and (ii) the abundances of accelerated heavy ions (Ne, Mg, Si, Fe) relative to the abundances of accelerated oxygen nuclei are enhanced relative to the coronal composition as is also observed in the composition of solar energetic particle impulsive events (Reames et al. 1994). The second study based on PHEBUS/GRANAT observations of the behind-the-limb flare of 1 June 1991 shows moreover that these enhancements in accelerated heavy ions increase with time in the flare, reaching towards the end the highest values observed in space for impulsive solar energetic particle events (Trottet et al. 1996; Ramaty et al. 1997). The analysis of the broad lines is probably made easier for this flare because of the occultation of the thick target part of the emission usually produced in the chromosphere. The continuum as well as the GRL emission comes indeed from the low corona at an altitude of at least 3000 km above the photosphere (Barat et al. 1994) and are produced by thin target interaction of accelerated particles in the corona. This thin target interaction is required to account for the very high observed ratio of the nuclear line emission in the 1.1-1.8 MeV range produced from deexcitations from Ne to Fe ions compared to the 4.1-7.6 MeV one produced by deexcitation of C to O ions. Indeed, in the case of a thick target production, accelerated particles lose energy while producing gamma-rays. As Coulomb energy losses are dependant on Z^2/A (Z nuclear charge number; A mass number), they reduce in a thick target production mode the importance of broad lines due to heavy ions with respect to broad lines produced by the lighter ions as well as the importance of the broad lines with respect to narrow ones (Ramaty et al. 1997). The high value of the ratio of the 1.1-1.8 MeV flux to the 4.1-7.6 MeV flux requires also that the composition of the accelerated particles exhibits heavy-abundance enhancements. Furthermore the increase of this ratio with time suggests a further enrichment of the heavy nuclei abundances as the flare progresses. Such an evolution may result from an evolution of resonant wave-particle interactions (see e.g. Miller, Reames 1996).

Although associated with a behind-the-limb flare, this event produced one of the largest GRL fluences observed so far and is associated with an ion energy content which although probably constituting only a fraction of the flare total energy exceeds the values found in most of the GRL flares observed on the solar disk (see figure 2). This flare is also associated with the observation of a strong flux of neutrons by the OSSE experiment (Murphy et al. 1999). As with the GRL emission, these neutrons are believed to be produced by thin target interactions in the solar corona. The comparison of the 1 June 1991 gamma-ray and neutron fluences with similar quantities observed by OSSE for the other large flare of 4 June 1991 (see figure 2 and Murphy et al. 1997; 1999) implies a very hard ion spectrum (power law index around -2) to account for the number of neutrons if they are produced by thin target interactions in the corona. It is finally worthwhile noting that such a hard ion spectrum is consistent with what is deduced from the ratio of the 1.1-1.8 MeV to the 4.1-7.6 MeV fluxes at least during the most intense part of the event (between -2 and -2.5).

5. Electron and Ion Energy Contents in Electron Dominated Events?

As shown in section 3, although comparable electron and ion energy contents are found in GRL events, some variability of the bremsstrahlung component compared to the nuclear line component is however found from one flare to the other or even during a flare (Chupp et al. 1993; Marschhäuser et al. 1994). Extreme cases of such variability can occur in the short duration (a few seconds to a few tens of seconds) bremsstrahlung ($\geq$ 10 MeV) transient bursts observed any time during a flare and referred to as electron-dominated events (Rieger, Marschhäuser 1990; Rieger 1994). They are characterized by weak or no detectable GRL emission and by hard $\geq$ 1 MeV electron bremsstrahlung spectra. They were first reported from SMM/GRS observations (Rieger, Marschhäuser 1990; Vestrand et al. 1991) and were afterwards observed by GAMMA1 (Akimov et al. 1991; Leikov et al. 1993), by PHEBUS and SIGMA experiments aboard GRANAT (Pelaez et al. 1992; Vilmer et al. 1994), GRO,(e.g. Dingus et al. 1994) and YOHKOH (e.g. Yoshimori et al., this volume). Rieger et al. (1998) performed spectral analysis for 12 electron-dominated events observed by GRS/SMM. They confirm the hardness of the bremsstrahlung spectra above 1 MeV (mean value of the spectral index around -1.84). The mean value of the continuum spectral index between 0.3 and 1 MeV ($\simeq$ -2.7) does not however differ significantly from that of other flares. The apparent lack of GRL

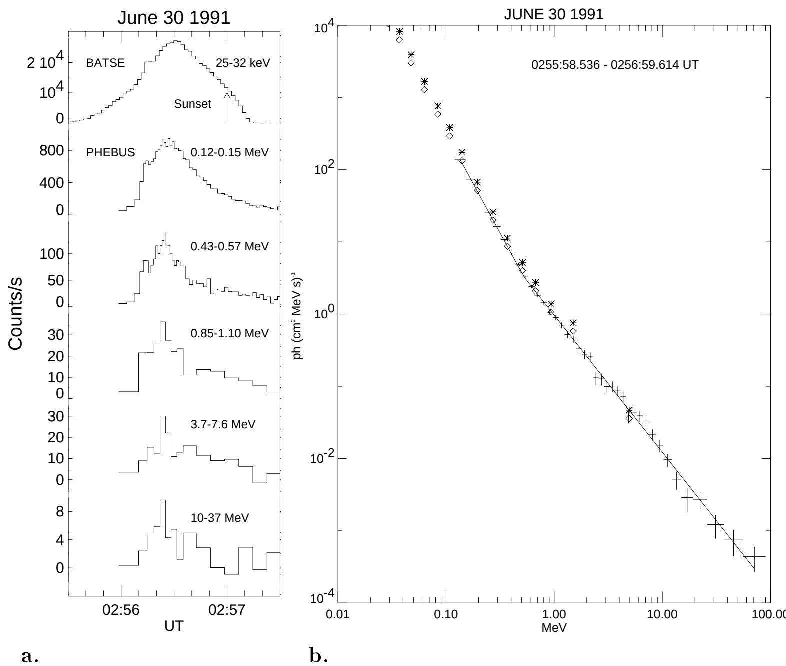

Fig. 3.. (from Vilmer et al. 1999) Time profiles of the 30 June 1991 event measured with BATSE and PHEBUS/GRANAT (a). HXR/GR photon spectrum observed by PHEBUS (error bars). The solid curve represents the best fit double power law spectrum. The stars represent the photon spectrum deduced from BATSE. The diamonds represent the same quantity divided by 1.3(b).

emission or weak production in these bursts do not necessarily contradict a simultaneous production of electrons and ions, and as discussed in Cliver et al. (1994), these events do not constitute a special class of bursts. Recent studies performed on two electron-dominated events observed by PHEBUS/GRANAT (Trottet et al. 1998; Vilmer et al. 1999) have shown that the near energy equipartition between electrons and ions found for strong GRL events can still hold for electron-dominated ones. Figure 3a and b shows the combined observations with BATSE and PHEBUS of one of these events associated with a behind the limb optical flare. The HXR/GR spectrum observed from 30 keV to 100 MeV is well described during most of the event by a double power law with a slope in the low energy part of the spectrum of -2.8 and a hard slope of -1.9 above a break energy of 0.53 MeV. There is no significant excess ($\geq 3\ \sigma$) above the expected power law spectrum in the 1-8 MeV range. An energy contained in ≥ 1 MeV/nuc ions around 4 10^{29} ergs , i.e. comparable to the energy contained in electrons above 20 keV would not however produce a GRL fluence being significantly detected by PHEBUS ($\geq 3\ \sigma$ above the continuum) (Vilmer et al. 1999). This is also found for the event of 11 June 1990 discussed in next section (Trottet et al. 1998). In conclusion, the near equipartition in energy between electrons above 20 keV and ions above 1 MeV/nuc found for strong GRL flares seems to hold for electron-dominated events as well, indicating that these bursts may be considered as weak GRL flares. The hardness of the bremsstrahlung continuum above 1 MeV may simply reduce the contrast of the GRL lines implying a more difficult detection. In the future, observations performed with a higher spectral resolution e.g. with the HESSI experiment (e.g. Hurford et al., this volume) should clarify this point by increasing the line sensitivity with respect to the continuum.

6. Bremsstrahlung and Synchrotron Emitting Electrons

Complementary observations of energetic electrons are provided by the gyrosynchrotron emission that they produce in the low corona at centimeter/millimeter wavelengths. We shall focus here on some results related to the comparison of bremsstrahlung and gyrosynchrotron emitting electrons obtained from the observations of HXR/GR spectra over a wide energy band and of centimeter/millimeter radiation in a wide frequency range. This topic is extensively discussed in these proceedings (see e.g. White; Silva et al. this volume). As shown in figure 3b, a spectral hardening of the photon spectrum above a few hundred keV is observed in some events. This was already reported for a few

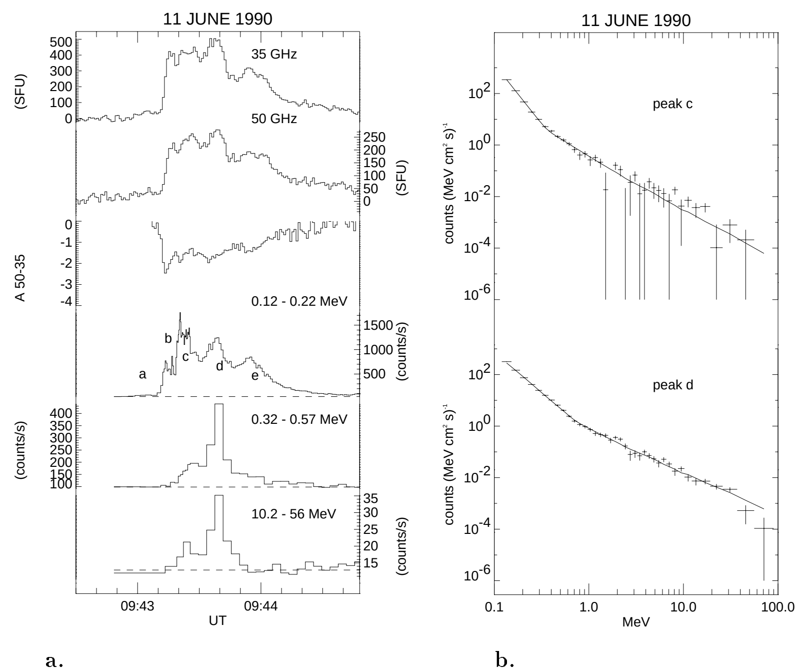

Fig. 4.. (adapted from Trottet et al. 1998) Time profiles of the 11 June 1990 event measured in three energy bands (bottom) with PHEBUS/GRANAT and at two microwave frequencies with the Bern polarimeters (top). Also shown in the middle, the power law index of the centimetric-millimetric spectrum between 35 and 50 GHz (a). Background HXR/GR count spectra observed by PHEBUS during peaks c and d. The solid lines represent the best fit models (b).

events observed by SMM (see e.g. Dennis 1988; Marschhäuser et al. 1994) or Hinotori (Yoshimori 1989) and even for a GRL flare observed by PHEBUS (Barat et al. 1994). Figure 4b shows other examples of such a clear spectral hardening observed for two time intervals of an electron-dominated event (Trottet et al. 1998). The time evolution of the HXR/GR count-rates (Figure 5a) shows that among the four most intense peaks labelled b,c,d,e, peak d exhibits the most intense emission above 10 MeV. During peaks c,d,e where significant ≥ 1 MeV emission is observed the photon spectrum is represented by a double power law. The photon spectra during peaks c and e are similar, with a break energy E_b around 0.36 MeV, a spectral index γ_1 below E_b of around -4 .4 and γ_2 above E_b of around -2.0 (Trottet et al. 1998, see e.g. figure 4b). During peak d, E_b is shifted towards a significantly higher energy (0.74 MeV) and the spectrum is harder, the larger hardening occurring below E_b (γ_1 = -2.9; γ_2= -1.7). During peaks a and b significant emission is only observed at low energies and no spectral hardening of the photon spectrum can be measured. The low energy part of the spectrum has a slope around -4. This HXR/GR event is associated with a centimeter/millimeter emission observed in the 3-50 GHz range during most of the event (figure 4a). While peaks b,c,d and e are clearly seen at both 35 and 50 GHz, peak a is detected up to 35 GHz and barely visible at 50 GHz. For most of the event (from $\simeq$ 0943 UT to $\simeq$ 0944 UT), the microwave emission is characterized by a turnover frequency between 11.8 and 19.6 GHz. As shown on figure 4a, the microwave spectrum is characterized by a spectral index (A50-35) between 35 and 50 GHz which is around -1.5 during peaks b,c,d and e. During peak a, the microwave spectral index between 19.6 GHz and 35 GHz is also $\simeq$ -1.5. Simple attempts to relate the spectral slopes of bremsstrahlung and synchrotron emitting electrons have been performed in Trottet et al. (1998) and the following conclusions have been reached: (i) for most of the event (peaks c,d,e), the centimeter/millimeter emitting electrons must be related to those emitting the HXR/GR emission above E_b, the lower energy part of the HXR/GR spectrum being much too steep; (ii) the values of the microwave spectral indices observed during peaks b and even a indicate that the high energy electron component clearly detected during peaks c,d,e is already present at the beginning of the event, even if it is too faint to produce a detectable HXR/GR emission. The above results bring observational support to the suggestions made by many authors (e.g. White, Kundu 1992; Kundu et al. 1994; Silva et al. and White this volume) that: (i) millimeter wave emission is produced by high energy electrons (above or around 1 MeV) characterized by a spectrum much flatter than the one deduced from X-ray observations around

100 keV; (ii) the high energy population as detected by centimeter/millimeter emission may be produced at the very beginning of the flare, even if the number of high energy electrons is too small to generate a detectable high energy HXR/GR signature.

7. Conclusions and Prospective

Some aspects of the high energy HXR/GR emission observed in solar flares have been reviewed in this paper with emphasis on the quantitative constraints that can be derived for the energy spectra and numbers of the accelerated emitting particles, on the respective energy contents of electrons and ions as well as on the composition of accelerated ions. Recent results include the following:

- There is a near equipartition in energy between electrons above 20 keV and ions above 1 MeV/nuc in strong GRL flares. In some cases, the energy contained in ions overwhelms that contained in electrons, suggesting that ions may even be energetically dominant in flares. Some variability of the relative numbers of emitting electrons and ions are however observed from flare to flare or even during a given flare. Even in the extreme cases of "electron-dominated" events, this near equipartition can still hold, indicating that these events can be considered as weak GRL events: even if no significant GRL emission is observed, the upper limit to the ion energy content can still be comparable to the energy contained in electrons above 20 keV, the lack of significant GRL emission being potentially attributed to the hardness of the electron bremsstrahlung above 1 MeV found for these events. This should be further investigated with observations obtained with a higher spectral resolution (i.e., an improved sensitivity to lines) such as the ones which will be obtained by HESSI in the next solar cycle.

- Accelerated ions exhibit enhanced abundances in heavy ions such as (Ne, Mg, Si, Fe) compared to the coronal abundances of these elements. This seems to be a characteristic of acceleration via resonant wave-particle interaction. Furthermore, in one large event, the enhancements of accelerated heavy ions increase with time and reach towards the end of the flare the highest values observed for interplanetary solar energetic particles. Further observations are certainly needed to establish if it is a common feature in flares.

- HXR/GR spectral observations performed over a wide energy band have shown, in some events, a clear hardening of the photon spectrum above a few hundred keV. These observations allow us to understand the relationship between millimeter/centimeter gyrosynchrotron emitting electrons and the high energy (above $\simeq$ 0.5 MeV) bremsstrahlung emitting ones. At present, observations do not allow us to examine whether the electron populations observed at low and high energies result from the same acceleration process or whether they constitute independent accelerated populations. In the future, the possibility of spatially resolving the bremsstrahlung components below and above the spectral break and the comparison with images of the microwave sources will provide new clues to understand this relationship. This will be possible with e.g. combined observations of the Nobeyama Radioheliograph and of the HESSI (High Energy Solar Spectroscopic Imager) experiment.

Finally, the variations of energetic particle spectra and relative numbers in the course of flares which have been shown to be associated with changes of the magnetic structures at different scales (see e.g. Chupp et al. 1993) should be further investigated with all the available radio, HXR and GR observations to better understand the link between the characteristics of the magnetic structures and the particle acceleration efficiency.

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