Energetic Particles in Solar and Stellar Coronae

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Abstract. Issues concerning the roles of energetic particles in energy transport in solar and stellar coronae, both flaring and quiet, are briefly reviewed. Ongoing controversies over electrons versus ions and nonthermal versus thermal transport in flares are indicated and the role which the HESSI Mission may play in resolving them is emphasised. Recent evidence from SoHO that nonthermal processes might be central also to mass supply of the quiet corona and wind via micro-evaporation events is summarised. The power required to supply the wind mass loss rate by bursts of micro-event evaporation is estimated and found to be large compared to other corona and wind power requirements. It is shown that if this power came from nonthermal electrons (> 5 keV) the resulting whole sun Hard X-ray flux should be detectable by HESSI unless the particle spectral index is large.

1. Introduction

Solar physics has always led the way in astronomical instrumentation and the excitement being enjoyed by stellar coronal researchers at the fabulous data from Chandra and XMM is akin to that of solar researchers in the previous decades. It is unfortunate that launch delays have prevented presentation here of results from NASA's HESSI Mission, the latest leap forward in high energy astronomical instrumentation, yielding the first ever joint high spatial and spectral resolution at hard photon energies (Lin 2001). In this paper the prospects for what HESSI may reveal are discussed against the background of 3 solar cycles of solar high energy particle studies from OGO and ESRO TD1A through Skylab, SMM and Hinotori to Granat, YohKoh and Compton GRO, as well as contextual plasma information from SoHO and TRACE. The advent of Chandra and XMM, though not yielding high energy data as such, is greatly advancing our knowledge of analogous stellar problems and processes, as described by others (especially Guedel) in these proceedings.
2. Energetic Particles in Solar Flares

2.1. General Points

The emphasis here is on evidence over whether, and which species of, energetic particles play a key role in flare impulsive phase energy transport. Pre-flare and main/gradual phase issues are not considered though some particle contribution may be present there. Pre-flare heating may also offer vital clues to how particle acceleration comes about, just as more information on a bomb is available by inspecting it before rather than after it detonates! Likewise, only brief mention is made of the extensive radio burst data available since the source particles are energetically secondary though of great importance as particle and plasma diagnostics, and useful proxies in the absence of hard X-Ray (HXR) data (cf Guedel, these proceedings).

Feynman (1998) reminds us that it is our duty as scientists to prove ourselves wrong as quickly as possible. The fact that the concept of a key flare energy transport role for particles has not been negated after half a century (Giovannelli 1946, Ellison & Hoyle 1948, Dubov 1963, Elliot 1964, Brown 1971,73, Lin & Hudson 1976) suggests there may be something in it, despite the scorn of sceptics. For example, at this meeting and elsewhere Feldman has denied the reality of the Neupert Effect (see below) while Guedel has presented beautiful examples of it. Feldman spoke of "copious particles accelerated in the corona by some unspecified magic trick". While the physics of particle acceleration (Cargill 2001) is as yet a poorly understood 'magic trick', the simple fact of energy conservation is enlightening. Release of free magnetic energy corresponding to that in a field $B = 100B_2$ g in a plasma of particle density $n = 10^{10}n_{10}$ cm$^{-3}$ provides a mean energy per particle of $\bar{E} = B^2/(8\pi n) \approx 25$ keV $\times B_2^2/n_{10}$ and if the total energy release is $\mathcal{E} = 10^{32}$ ergs $\times \varepsilon_{32}$ the number of particles affected is $N = n\mathcal{E}/(B^2/(8\pi)) = 2.5 \times 10^{39} \times n_{10}\varepsilon_{32}/B_2^2$. These numbers are amazingly similar to those inferred from a nonthermal electron interpretation of large HXR bursts (Hoyng et al. 1976).

2.2. Energetic Flare Electrons

The idealised data diagnostic problem here is the inference of the electron distribution function $f_e$ in velocity, space and time from HXR bremsstrahlung photon data. Besides line of sight ambiguity, such recovery is limited by the spatial, temporal and spectral resolution of HXR instruments (at energies well above those of Chandra and XMM) and by the rapid decline of photon flux with increasing energy. The latter acts as a noise source amplified by the intrinsic instability (Craig & Brown 1986, Piana 1994, Thompson et al. 1992, Johns & Lin 1992) of the spatial and spectral deconvolution problems involved. The problem is compounded by the influence of beam propagation processes in the plasma. The nature of some of these is unknown while other well defined energy loss effects, such as that of atmospheric ionisation structure (Brown et al. 1997) and wave generation (Haydock et al. 2001) can render the inversion of spatially integrated spectra (e.g. Lin & Schwartz, 1987) analytically non-unique in the electron spectrum domain! HESSI's unprecedented high spatial and spectral resolution should help unravel these ambiguities in $f$ (Emslie, Barrett & Brown 2001).
The central question is really the transition energy $E_c$ above which the source $f$ ceases to be locally Maxwellian in the primary energisation region. At energies $E \leq E_c$ collisional energy exchange between electrons is small, the main energy loss is e-p bremsstrahlung, and (thermal) HXR production is very efficient, requiring little energy in those electrons. At energies $E \gg E_c$ the electrons escape and propagate through a relatively cold background plasma in which the main energy loss is by collisional e-e plasma heating and (collisional thick target) HXR production is very inefficient, requiring a lot of energy in those electrons. Typical HXR data indicate that if $E_c < 20$ keV or so then the high energy 'tail' component carries a large fraction of the impulsive flare power (Brown 1971 and many subsequent authors). Thus the practical problem is to try to find any spatial, spectral or temporal signature in the HXR bremsstrahlung which might indicate a real change in the nature of $f(v)$ at some $E_c$ – cf. Johns & Lin (1992). Spatially integrated spectra confuse, by mingling, the efficient thermal emission for a tenuous acceleration region with the inefficient nonthermal emission from a dense region, and only spatially resolved spectra such as from HESSI are likely to progress the question beyond current indirect evidence such as:

1. The Neupert effect (Neupert 1968) – the tendency for thermal SXR light curves to follow the time integral of HXR light curves, or their radio proxies especially in the case of stars (Guedel – these proceedings). This suggests that the power going into the hot plasma and that going into the energetic electrons are closely linked even if HXR source electrons do not actually transport the primary power into the SXR plasma.

2. The degree of synchronism of impulsive thermal emissions at various wavelengths/locations (Woodgate et al. 1984) and of HXR emissions at distinct 'footpoints' (Sakao 1994), and the cospatiality of some HXR features with thermal emissions (Fletcher et al. 2000, Fletcher & Hudson 2001) are hard to explain unless energetic electrons (or ions) are in fact the power source of all of them since there is no other obvious means to propagate energy so fast (the Alfven speed is too low – e.g. MacKinnon et al. 1986)

3. Cases of simultaneous emission of HXRs at high and low altitudes (Masuda et al. 1994) and the consistent interpretation of energy dependent HXR delays as electron time of flight effects along flux tubes of the lengths observed (Aschwanden et. al 1996), is supportive of the dominance of the nonthermal part of $f$ at electron energies ($> 20$ keV) able to reach the chromosphere

Regarding 2) and 3) above, an important proviso is that neither the reported degree of synchronism nor the energy dependent delays is based on timings of individual features but rather only on cross-correlation over event durations. Until data are adequate for timing comparisons of individual features one must be cautious about systematic bias in time averaged cross-correlations.

Despite all this ambiguity, two things are clear. First, whether or not deka-keV electrons carry a lot of the impulsive phase flare power, many of them are accelerated in the primary magnetic energy release and not, as one questioner at these proceedings suggested, a secondary product of shocks arising from primary heating – HXRs precede rather than following shocks. The same is true
of impulsive phase ions as evidenced by gamma-ray lines. (There may, however, be additional particle acceleration by shocks as the gradual phase progresses). Secondly, if energetic electrons (or ions) do account for a large fraction of magnetic energy release, the acceleration mechanism involved has to be very energy efficient. On the other hand, the oft cited 'number problem' (e.g. Simnett 1995) as an objection to electron beam models is a myth which refuses to die. It is true that the nonthermal beam interpretation (Brown 1971) of HXRs does involve the processing of more electrons than exist in a coronal loop but it is basic fact of beam physics (Miller 1982, Spicer & Sudan 1984, Knight & Sturrock 1977, Hoyng et al. 1976) that a beam in a plasma creates, on very short timescales, a plasma drift return current which recirculates electrons up the loop. This is an electrodynamic effect on electrons and nothing to do with the much slower thermally driven gasdynamic evaporative upflow. Residual problems, however, are that the return current has to be highly filamented (Holman & Benka 1993) and can become unstable (e.g. Cromwell, McQuillan & Brown 1988). There is a vast literature on particle acceleration – readers interested in recent ideas might usefully start with references in Cargill (2000) and Vogt et al. (2001).

2.3. Energetic Flare Ions

Extensive studies have been carried out of flare ions using the gamma-ray lines and continuum, and also the neutrons, they produce – see references in Ramaty et al. (1996), Ramaty & Mandzhavidze (2001) for example. There is a near total lack of information on spatial structure (which HESSI will remedy) but gamma rays from events which are long enduring or associated with flares behind the limb indicate that sometimes energetic ions reside high in the corona. On the other hand, the detection of neutron capture lines requires much of the impulsive emission to occur in very dense low layers of the atmosphere. Careful modelling of the line fluxes and continuum leads to valuable abundance information and the ion distribution function spectral shape down to around 1 MeV. This was thought to flatten out at the low end so that the extrapolated total energy was believed to be only modest. However, recent analyses of new data (Ramaty & Mandzhavidze 2001) suggest otherwise and open up hopes for proponents (e.g. Simnett 1995) of the ion-dominated model of flare energy transport. If the ion spectrum extends as a power law much below 1 MeV then the energy content in the 100 keV range could be a significant fraction of that in the impulsive flare. The value of \( E_c \) for ions is even more uncertain than for electrons, the only source of data on 100 keV ions being H\( \alpha \) impact polarisation. The interpretation of available data is so far unclear and in any case is more sensitive to the target atmosphere model than to the beam flux (Vogt et al. 2000). Simultaneous HESSI and H\( \alpha \) impact polarisation imaging should advance understanding here.

Even if ions do prove to be important in the overall flare energy budget, the problem of HXR production remains and the circumstantial evidence, summarised in Sec. 2.3, that electron beams are energetically important can only be countered if alternative mechanisms for it and for HXR production can be found. Options (cf. Tatischeff et al. 1998) include HXR emitting electrons being driven by an ion beam (Heristchi 1987) or a neutral beam (Simnett and Haines 1990, Karlicky et al. 1998, Brown et al. 2000a). The latter is the more promising but versions to date yield too few HXRs.
3. Non-thermal Micro-events and Coronal Mass Supply

Many authors have worked recently on the idea that coronal heating may result from large numbers of small magnetic energy release events termed micro- or nano-flares according to their sizes, which have a roughly power-law frequency distribution (see e.g. Benz & Krucker 1999, Krucker & Benz 2000 for references). Much of this work has been statistical in character with comparatively little on the physical nature of the events (cf. Klimchuk & Cargill 2001, Vekstein & Katsumawa 2000). These events involve changes in loop emission measures as well as temperatures and Brown et al. (2000b) have emphasised that it is as important to consider the problem of mass supply as that of heating. The usual tacit assumption has been that if a coronal loop undergoes a heating event the resulting conductive flux downward will cause enough mass upflow by radiative instability and chromospheric evaporation (Sweet 1969, Brown 1973, Antiochos & Sturrock 1978) to provide the emission measure enhancement. Using the Rosner et al. (1975) conductive scaling laws, Brown et al. (2000b) have shown that this is not the case – in the SoHO EIT events analysed, temperature rises are inadequate to explain emission measure rises solely by conduction and concluded that additional nonthermal heating of the upper chromosphere is required. By generalising Brown’s (1973) treatment of flare evaporation to small energy fluxes, they assessed the nonthermal energy fluxes required to explain one of the larger SoHO EIT events. They did not advocate any particular form for the nonthermal heating source but suggested that if it were energetic (few keV) electrons, accelerated as part of a magnetic energy release event in the corona, then the resulting low energy HXR flux from the many events typical present on the sun might be detectable by HESSI.

Noting that the total mass supply rate to the corona must be at least enough to supply the wind mass loss rate $\dot{M}_{\text{wind}}$, Brown, O’Malley, & Smolkin (2002) have pursued this and evaluated the total nonthermal power $P$ needed to evaporate matter at this mean rate in an ensemble of micro-events over the sun. The value depends on:

1. the spectral index $\delta$ describing the heating depth scale of the energy input. Larger $\delta$ corresponds to greater concentration of the heating in the top layers of the chromosphere and, in the case of energetic particle heating is the usual particle energy flux spectral index.

2. the area $A$ over which $P$ is distributed. Increasing $A$ increases the evaporated area but reduces the heating flux for given $P$ and hence the depth of evaporation.

3. the duration $\Delta t$ of each of the events (which are treated as identical). If $\Delta t$ could be made very small then the evaporation could occur so fast that there would be negligible radiative energy losses as plasma passed through the radiative loss function peak at around 60,000 K. Then the only power involved would be that to raise the temperature and altitude of the evaporated matter to coronal values – roughly $\dot{M} \times (kT_e/m_p + g_{\odot}R_{\odot})$. In practice the upflow must take around a hydrodynamic time $\approx 100$ s and so there is a larger power requirement to offset the radiative cooling as matter passe through the 100,000 K region.
Preliminary results yield an alarmingly high value of $P \geq 6 \times 10^{27}$ erg s$^{-1}$ for $\delta \leq 7$. The figure falls with increasing $\delta$ but cannot be made arbitrarily small since increasing $\delta$ requires increasing $A$ to yield the same evaporation rate. $A$ certainly cannot exceed $4\pi R_0^2$, and is likely to be much smaller, concentrated in loops. In practice, because much material falls back the evaporation rate will have to be $\gg M_{\text{wind}}$ and $P$ correspondingly higher still.

Attributing the $P$ required to evaporate $M_{\text{wind}}$ to nonthermal electrons, Brown et al. (2002) also estimated the HXR ($\geq 5$ keV) flux expected at the earth and found that if $\delta \leq 5$ or so, this should be easily detectable by HESSI but might escape detection if $\delta \gg 5$. A high value of $\delta$ would be consistent with the finding of Benz and Krucker (1998) that in the correlation of heating event nonthermal radio flux versus SXR flux, there is a drop below the correlation line at small fluxes – i.e. small events are radio weak – an effect attributable to large $\delta$. Detection hitherto of any HXR flux associated with such solar wind evaporation by nonthermal electron events would not be expected since pre-HESSI instruments have strongly attenuated signals at energies below around 10 keV.

4. Conclusions

Nonthermal particles continue to occupy a central place on the stage of solar and stellar flare energy transport studies, and may also be implicated in the heating and mass supply of quiet coronae and winds. HESSI should offer major steps forward in resolving some of the controversial issues in the role of energetic electrons and ions on the sun. Chandra and XMM results presented here are allowing stellar flare physics to follow closely on the heels of solar physics and hopefully future missions will extend stellar studies to high energies, using HESSI style instrumentation. Finally, it is worth noting that the presence of nonthermal particles in stellar coronae and winds could be one factor in explaining the recent paradoxical results from Chandra and XMM on density sensitive line ratios (e.g Waldron and Cassinelli 2001)

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