SH 1.2-13

A DOMINANT ROLE FOR PROTONS AT THE ONSET OF SOLAR FLARES

G.M.Simnett
Department of Space Research, University of Birmingham, U.K.

ABSTRACT

We suggest that recent observations have cast considerable doubt on the generally accepted explanation that non-thermal electron beams transfer most of the flare energy during the onset of solar flares. In this paper we argue that non-thermal protons in the energy region 10^2-10^3 keV are a more probable energy transfer mechanism. An important consequence of this hypothesis is that the hard X-ray burst must be thermal.

1.Introduction It was shown many years ago(1) that the energy released in a solar flare was consistent with the total energy in non-thermal electrons above 20 keV, assumed to be responsible for the hard X-ray burst via non-thermal bremsstrahlung in a thick target. Since that time support for this hypothesis has grown to the extent that many regard it as an established fact. For example, it has recently been stated(2) that to account for many large flares no significant energy input, other than electrons > 25 keV, needs to be invoked. In another recent paper(3) it was argued that over 10^{36} electrons.s^{-1} were required during the impulsive phase of the 1981 April 24 flare.

We believe that improved observations made during the last solar maximum have cast doubt over this interpretation of the impulsive phase of flares. Among the more significant observations are the following:

a) The high plasma turbulence seen in heavy ions, eg Ca$\overline{\underline{XIX}}$, prior to the onset of the hard X-ray burst, including in some cases significant mass upflows(2,4).

b) The presence of high energy protons at the onset of the impulsive phase of some gamma ray flares(5,6).

c) The complete absence of metric/decimetric radio emissions during many large flares including the impulsive phase of the 1981 April 24 flare(7).

When the energy inputs required for a) and b) are taken into account, together with the energy in the whole electron spectrum, the total flare energy budget becomes heavily oversubscribed. In addition, if the efficiencies of the acceleration processes are also considered, which are quite probably less than 50%, the situation is even worse. Thus another significant point is:

d) When the energy in the pre-impulsive phase plasma turbulence and upflows is added to the energy in the non-thermal electrons and ions, together with an efficiency factor, the flare energy budget appears to be exceeded.

To overcome these problems an alternative hypothesis is suggested, namely that the primary energy release results in the coronal acceleration of non-thermal protons which have the bulk of their energy in the 10^2-10^3 keV region. We shall show that this offers an attractive alternative to both the non-thermal electron hypothesis discussed above and the alternative thermal models suggested recently(8,9). Our model is essentially a non-thermal proton model which results in excessive heating of the chromosheric plasma to produce the hard X-ray burst by thermal bremsstrahlung.

2.The Non-Thermal Proton Hypothesis

We now consider the four points a)-d) mentioned above in more detail.

a) The plasma turbulence and upflows observed before the onset of the hard X-ray burst cannot be caused by the impact of electron beams on the chromosphere without producing X-rays. As soon as an electron beam is accelerated a reverse current will be set up to avoid charge separation. Emslie(10) has shown that when reverse current losses of the beam are taken into account the electron energy must exceed $\sim$60 keV to penetrate below the transition zone for any reasonable atmospheric model. Theory has shown(11) that energy must be dumped below the transition zone for significant mass to be ablated.

Protons in the region 10^2-10^3 keV can do this readily. Depending on the atmospheric model the threshold energy for penetration to the top of the chromosphere from the corona is 400±150 keV, with the lower limit probably more appropriate to the onset of a flare. Reverse current losses are largely eliminated by having accompanying electrons of the same velocity as the protons. The energy content of sucn electrons is negligible compared with the protons.

b) Gamma ray production at the flare onset is accounted for by a slightly more efficient acceleration process which raises the high energy tail of the proton energy spectrum. This need only have a minor effect on the total energy of the accelerated protons, which explains in a natural way why many gamma ray flares are optically small, with relatively low total energy. On the conventional model, if the typical flare is dominated energetically by non-thermal electrons then the gamma ray flares must invoke a proton acceleration process which suddenly becomes important. We believe such a scenario is unattractive.

c) Radio emission is an important electron signature. In a magnetic field relativistic electrons emit gyrosynchrotron radiation, which in the flare situation appears in the microwave region. An electron beam with a velocity distribution increasing towards high energies will emit plasma radiation; such beams are frequently observed as type III bursts and only $\sim 10^{29}$ electrons $>$20keV are required for these to be detectable by modern radio-telescopes. Correlation of microwave bursts with hard X-rays is very high; virtually 100% for bursts $>$1000 counts.s^{-1} detected by the Hard X-Ray Burst Spectrometer on SMM. Yet 15% (7) of the same flares have no metric/decimetric radio emission.

It might be argued that the required velocity distribution in the electron beam builds up too slowly for a type III burst to be produced. However, observations(12) of very fast ($\ll$1s) hard X-ray fluctuations argue just the opposite, namely that the release must be impulsive unless the acceleration site is very close, $\sim 10^3$km, to the chromosphere. Hard X-ray imaging observations from SMM suggest that such small distances are unlikely in a typical flare (13).

The impulsive phase of the white-light flare on 1981 April 24 had 35 GHz emission of $\sim 5000.10^4$ Jy(3). Microwave emission at this level occurred in only nine flares during 1979-82, so this is truly a major event. However, it produce no metric/decimetric emission until the onset of the gradual phase some 5m after the impulsive phase maximum. On the non-thermal electron hypothesis over 10^{36} electrons.s^{-1} are required to produce the X-rays and the impulsive phase lasts for over 100s. It is very surprising that during this time enough electrons to produce a type III burst - 10^{29} - did not escape into the corona.

d) It has been proposed recently(2) that electrons $>$25 keV may provide the energy for the entire flare. This, however, neglects the energy in electrons $<$25 keV and there is no basis from observations to suggest that these electrons are negligible. In fact, to the contrary. Lin et al(14)made high spectral resolution observations of a flare which showed that the electron spectrum extended to 13 keV (the low energy cut-off of the measurement) without a change in spectral index. As the spectral index was -4.5 this implies an order of magnitude increase in energy content going from 25 keV to 10 keV. We have no way of estimating the proton energy spectrum at the Sun below $\sim$5 MeV. However, analysis of the 1972 August 4 flare(15) indicated over two orders of magnitude more protons than electrons at 5 MeV and extrapolation of the spectrum produced equal numbers of protons and electrons at 40 keV. While there is no basis in this flare for such an extrapolation, it shows proton energy should not be disregarded. The accelerator is presumably $<$100% efficient at producing non-thermal particles. Even if we assume 50% efficiency, it appears that we would have no difficulty in estimating a total energy which is a factor of 20-40 higher than that contained in electrons above 25 keV.

From the above there is no doubt that the arguments for the total flare energy residing in non-thermal electrons $>$25 keV are weak and that there is substantial evidence against their existence in any energetically-dominant form at all. It now remains for us to show that non-thermal protons can explain the phenomena better. Protons of a few 100 keV can readily drive the plasma turbulence and ablation without producing hard X-rays. They are necessary for the gamma rays, and they can easily heat the chromosheric plasma to produce the soft X-ray emission. The principal difficulty with a proton beam is in hard X-ray generation. To do this there must be rapid heating in a way that produces electron temperatures significantly above ion temperatures. Such a mechanism has been suggested in the context of Tokomaks(16), which invokes plasma instabilities in fine-scale filamentary structures where electron temperatures are enhanced by 10^2 or more. While this is probably not directly applicable to the flare situation, it indicates that anomalous effects are likely in plasmas with high beam currents and that extremes in temperature might occur.

In terms of energy, thermal hard X-ray production is ~30 times more efficient than a non-thermal process(17). In addition our model only requires one acceleration mechanism to be operating to account for all flares. There are other important observations, such as the insensitive way $O\underline{V}$ emission correlates with hard X-rays and the negative results from polarization studies that also argue against non-thermal electron dominance(18,19).

3. Conclusions. We have shown that there is considerable evidence against non-thermal electron beams as the dominant energy transfer mechanism during the impulsive phase of solar flares. Instead we suggest that non-thermal protons in the energy region 10^2-10^3 keV are a more likely energy carrier. The advantages of protons are that they can account for the plasma turbulence and upflows seen before the hard X-ray burst, they can produce gamma ray emission from optically weak flares and they can account for the lack of metric/decimetric emission in many large flares. In addition, only one acceleration process need be advocated to account for all flares provided it is approximately velocity dependent. Such a process is the MHD shock, which certainly has all the right properties when observed in interplanetary space. An important consequence of our model is that the hard X-ray burst must be thermal in the impulsive phase.

References

1)Lin R.P. and Hudson H.S.(1976) Sol Phys 50,153
2)Antonucci E. et al (1984) Ap J 287, 917
3)Kane S.R. et al (1985) Ap J 290, L45
4)Antonucci E. et al (1982) Sol Phys 78,107
5)Chupp E.L. et al (1982) Ap J 263, L95
6)Forrest D.J. et al (1981) Proc 17th Int Cosmic Ray Conf 10,5
7)Benz A.O. and Simnett G.M. (1985) (in preparation)
8)Brown J.C. et al (1979) Ap J 228, 592
9)Smith D.F. and Lilliequist C.G. (1979) Ap J 232, 582
10)Emslie A.G. (1980) Ap J 235, 1055
11)MacNeice P. et al (1984) Sol Phys 90, 357
12)Kiplinger A.L. et al (1984) Ap J 287, L105
13)Hoyng P. et al (1981) Ap J 246, L155
14)Lin R.P. et al (1981) Ap J 251, L109
15)Ramaty R. et al (1980) in "Solar Flares" ed P.A.Sturrock, Colorado Univ Press
16)Haines M.G. and Marsh F.J. (1982) J Plasma Phys 27, 427
17)Smith D.F. and Harmony D.W. (1982) Ap J 252, 800
18)Poland A.I. et al (1984) Ap J 280,457
19)Tramiel L.J. et al (1984) Ap J 280, 440