A NEW EXPLANATION FOR FLARES ON dMe STARS

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Abstract

It has been proposed that non-thermal ions dominate the energy transfer at the onset of solar flares. Here we examine this hypothesis in the context of flares on dMe stars. If the magnetic field in the stellar corona is significantly larger than that in the solar corona, and if strong fields in the photosphere, analagous to active regions, are absent, then a self-consistent explanation of stellar flares may be formulated.

1. Introduction

Understanding flares in flare stars is related intimately to understanding the energy transport from the magnetic field to the lower atmosphere. The only mechanisms considered by Haisch (1986) in his comments on solar-stellar flares were thick-target interactions by non-thermal electron beams, or thermal conduction. We believe another process is worth investigating. Simnett (1986) and Martens (1988) proposed that in transient energy releases in the corona the energy transfer medium from the magnetic field to the plasma is a neutral ion beam in which essentially all the energy resides in the ions (protons). With this concept the ions predominantly *heat* the atmosphere, which would manifest itself in enhanced U-band emission. The production of X-rays is incidental to this heating as the ions normally deposit most of their energy via Coulomb collisions. In the Sun the sudden density increase at the transition region, coupled with the column depth of the transition region from the corona, produces conditions appropriate for the generation of the X-ray burst. In dMe stars the physical conditions are different and the X-ray signatures are relatively weaker than in the Sun.

2. The Important Properties of dMe Flare Stars

Properties of dMe stars that are relevant to this discussion are: the optical flare light curve; rapid rotation; strong coronal magnetic fields; and large-scale coronal magnetic loops. The U-band light curve of a typical flare in UV Ceti has a main phase of ~1m. Similarities between this timescale and that of a "typical" solar flare hard X-ray burst are apparent. We interpret the impulsive part of both as representative of the duration of energy deposition in the *chromosphere*; coronal heating may be over a much longer period.

The hot gas in the X-ray-emitting coronae of nearby dMe stars is contained by the coronal magnetic field and Rosner *et al.*, (1985) recognized in the solar case that this magnetic field is central both to quiescent X-ray emission and to flares. The generation of the magnetic field is attributed to a dynamo mechanism, sustained by having a convection zone in a rotating star. For stars of spectral type later than F, which have a convection zone, the quiescent X-ray luminosity $\propto$(rotation rate)^2 (Rosner *et al.*, 1985). For stars later than M5.5, ~100% of M dwarfs are dMe stars; they are generally small stars (0.1 $M_\odot$) and are probably fully convective. Thus we expect rotating dMe stars to have strong coronal fields. Giampapa and Rosner (1984) showed that stars with shallow convection zones, such as the Sun, should exhibit a significant reduction in the size of a typical active region. Such stars will have strong X-ray flares, compared with the magnitude of the energy release, as the small-scale field concentrates the energy flux better. Conversely, there will be lower quiescent X-ray emission as the large-scale coronal fields are lower, and can contain a lower matter density, which results in an overall low emission measure. The magnetic field strength is an important parameter, as it is the flare energy source and also restrains the accelerated ions such that they lose their energy in the stellar atmosphere. Strong solar fields, $\geq$0.1T, only exist, above the convection zone, in active regions, and coronal fields are very weak by comparison. On flare stars Mullan (1976) suggested 1T for an event from BY Dra, but more recently, estimates of the magnetic fields needed to account for microwave emission have been made which are smaller, ranging from 0.025T to 0.3T (Gary *et al.*, 1982; Kundu and Shevgaonkar, 1985; Bastian and Bookbinder, 1987).

EXOSAT observations reveal that coronae may extend to a stellar radius (White *et al.*, 1987) or to several stellar radii (Collier Cameron *et al.*, 1988). VLBI measurements of Algol (Hjellming, 1980) indicate that the size of the radio-emitting regions for strong events is 2-3 stellar radii. Kundu and Shevgaonkar (1985) infer sizes even larger, up to 6 stellar radii for YZ CMi. Occasionally loops extending to several $R_\odot$ are needed to account for solar phenomena (Leblanc and Hoyos, 1985). There is no evidence that such loops are permanent, although thay have been inferred to exist for as long as 5 days (Sinnett and Holt, 1971).

dMe stars have high quiescent X-ray luminosity, typically $>>10^{28}$ erg s^{-1} compared with the solar luminosity of $<10^{27}$ erg s^{-1}. As the effective X-ray temperatures are in the 10^6 $\geq 10^7$ K range then the increased luminosity, over the solar value, must be mainly due to an increased emission measure (n_e^2V). Thus either the coronal loops in flare stars are very large, or the coronal densities are high, or both.

In summary, it is evident that conditions on flare stars involve large coronal structures, with high magnetic field strengths. Within this framework, large, impulsive optical events are seen; but (see below) the soft X-ray events that are sometimes observed in coincidence tend to be more slowly varying.

3. Ion Acceleration

Fundamental to our hypothesis is the requirement that ion acceleration be a natural consequence of magnetic energy release. A likely acceleration mechanism is a magnetosonic shock, although as Martens (1988) has shown, direct electric field acceleration may also be satisfactory. In his review of shock formation and evolution in the solar atmosphere, Bougeret (1985) emphasized that shocks "are among the most dramatic and energetic phenomena of solar origin". Bougeret also notes that the majority (80%) of coronal type II radio bursts, which are caused by strong shocks moving up through the corona, are associated with sub flares or class 1 flares; therefore they are *not* an indication of a big flare.

Theoretically shock acceleration has been studied extensively (*e.g.* Decker and Vlahos, 1985; Ohsawa and Sakai, 1987). Ohsawa and Sakai show that ions are readily accelerated up to a velocity:

$$v \sim v_A (m_i/m_e)^{1/2} (M_A - 1)^{3/2}$$

where v_A is the Alfvén velocity and M_A is the Alfvén Mach number. For an Alfvén velocity of 400 km s^{-1} and $M_A = 3$, the proton energy is around 10 MeV. Electron acceleration in high-Mach-number shocks has been addressed by Tokar *et al.*, (1986) but they point out that even under the most favourable conditions it is difficult to put more than about 1% of the released energy into the electrons. Thus our conclusion is that ion acceleration is likely to dominate during any realistic shock acceleration process in the stellar context.

There are many examples of proton acceleration within the solar system, *e.g.*:

1. In the MeV region of the spectrum, high proton fluxes of solar origin are extremely common in the interplanetary medium. There is a solar cycle dependence and the flux is higher at solar maximum than at solar minimum. Around the last solar maximum, July December, 1979, the 0.97 - 1.85 MeV proton intensity was ≥ 10 protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} for 47.6 days out of 184. The largest "flare" associated events exceed this flux by over three orders of magnitude. By comparison, the lowest intensities recorded were $<10^{-2}$ protons cm^{-2} s^{-1} sr^{-1} MeV^{-1}, and this level was experienced on only a few days in this period. This illustrates the ease with which the Sun produces such particles. If we take 10 protons cm^{-2} s^{-1} sr^{-1} MeV^{-1} as typical of the coronal leakage, and assume that it is emitted isotropically with a spectrum such as that measured by Sanahuja *et al.*, 1983, then the energy flux in such particles is $\sim 10^{24}$ erg s^{-1}. This is only around three orders of magnitude less than the quiet time solar X-ray luminosity. The difference between the interplanetary proton flux ~1 MeV during quiet times and extreme flare periods is $\sim 10^6$. If energy release is occurring continuously via magnetic reconnection in the corona, then there will be continuous acceleration. The energy given to the protons must re-appear somewhere. It may be retained, but re-distributed, in the corona, thereby heating it; it may be transported and dumped in the chromosphere, thereby producing a "flare"; or it may be released into space. It is not difficult to imagine that the magnetic field plays an important role in controlling the destiny of this energy. What fraction of accelerated protons are detected in interplanetary space is an open question, and it is equally open as to the contribution such particles make to coronal heating. Energy deposition by accelerated ions is a plausible candidate for re-distributing the energy released by the coronal field into global heating of the coronal gas.

2. Some large low-energy (<2 MeV) proton events are associated only with disappearing filaments (*e.g.* Sanahuja *et al.*, 1983). We interpret these as events where the topology of the coronal field was inappropriate to contain the accelerated ions, so instead of producing a "flare" they escaped into space.

3. Trapped protons in the Jovian magnetosphere observed by spacecraft have a spectrum which flattens around 1 MeV (McDonald *et al.*, 1979). The bulk of the energy in such a spectrum is $\sim$0.1 1 MeV.

In summary, theoretical results have demonstrated the ease with which ions may be accelerated; this is not the case with electrons. The accelerated energy spectrum is a function of the shock parameters, but where direct observations can be made the bulk of the energy resides in protons in the 0.1 1 MeV region.

4. Relevance to Observations of Flares in dMe Stars

Several flare observations of dMe stars cover more than one wavelength band. A strong (3.5 10^{31}ergs), long-lived ($\sim$2 h) X-ray flare from Proxima Centauri (Haisch *et al.*, 1983) was observed both by *Einstein* and IUE. The IUE spectrum at the peak of the X-ray event showed considerably enhanced emission lines. Thus this flare could be interpreted as a large solar-type flare. Flares from UV Ceti, and other dMe stars, tend to be much shorter. The first co-ordinated optical and X-ray observations of a flare in UV Ceti (Heise *et al.*, 1975). showed that the optical light curve peaks earlier than the X-ray light curve and decays faster. A 5m-duration flare in YZ CMi (Doyle *et al.*, 1988) exhibited no correlated X-ray emission above the EXOSAT threshold; the only X-ray event close to the optical flare reached maximum 11m later. The lack of correlated X-ray activity for this flare completely eliminates any concept that the energy transfer is via electron beams.

We now examine how these observations are explained quite naturally by the following scenario. Suppose that energy release in the corona is tranferred to accelerated ions which move towards the chromosphere over a large area. (In this context "large" is in comparison with the fraction of the solar surface occupied by a solar active region. Recall that for stars with deep convection zones the size of any active region would be large compared with the solar case and therefore the energy deposition is likely to be more diffuse in a dMe star than in the Sun.) This will initially result in heating; hence the dramatic increase in the U-band emission. In high density regions and with low energy *flux* the temperature rise is offset by rapid cooling, so the plasma never reaches X-ray emitting temperatures. The heated material is driven into the stellar corona as an expanding, upward moving mass. Two things now happen; 1) the rising mass presents a high column density to ions in transit to the chromosphere from the corona; this column can absorb the energy of any accelerated ions (0.1 1 MeV) still being produced before reaching the chromosphere; this removes the driver for the evaporation; 2) the energy absorbed in the rising column of plasma heats it. The difference, however, from the initial situation is that the lower density results in a much longer cooling time. Provided energy is still fed in the temperature will rise to a value which may be high enough to emit X-rays.

We believe this explains quite naturally why the soft X-ray flux peaks after the optical flux, or why in some cases, if the energy release stops prematurely, it may be entirely absent. Also, if a fresh energy release occurs *before* the evaporated material has drained back to the base of the corona, the high density coronal gas may be heated to X-ray emitting temperatures without any noticeable effect in the chromosphere, which is presumed to be the primary site of the U-band flux. The observations of de Jager *et al.*, (1986) of activity in BY Dra are consistent with our thesis; in this event the bulk of the soft X-ray event occurred some 6m after the peak in the U-band flux.

We noted above that the quiescent X-ray luminosity is relatively high in dMe flare stars. This is interpreted as heating due to Coulomb collisions of ions which are, presumably, quasi-continuously being accelerated by the shocks induced by magnetic reconnection in the stellar corona. Stellar flares occur when the magnetic field geometry changes slightly to allow direct access of the accelerated ions to the chromosphere, or when the accelerator becomes slightly more effective in producing energetic ions and shifts the peak in the energy spectrum to higher energies, thereby allowing deeper penetration into the atmosphere. If the energy release is quasi-continuous, then the mean X-ray luminosity and the time-averaged flare energy are both likely to be correlated with the rate of energy release; it is merely dumped in a different part of the atmosphere. This correlation has been noted (Doyle and Butler, 1985).

There are relatively few co-ordinated radio observations of stellar flares. Papers on radio bursts from flare stars (*e.g.* Gary *et al.*, 1982; Kundu *et al.*, 1987) attribute much of the microwave emission to a coherent electron-cyclotron maser. There are, nevertheless, observations which do not seem to fall in this category (Bastian and Bookbinder, 1987). Although the impulsive flares they observed were attributed to a coherent emission mechanism, some slowly-varying emission was interpreted as gyro-synchrotron emission. Moreover, in the star they observed this was more than two orders of magnitude greater than similar solar emissions. These clearly need large numbers of electrons. However, this is not in conflict with our basic premise; we are not advocating that there are *no* electrons accelerated in flare stars, merely that in terms of the energy budget they are insignificant.

5. Predictions

In conclusion there are several predictions that are appropriate to make.

1. Red shifts in the line spectra. If an ion beam travels downwards and is stopped, due to charge-exchange there should be red-shifted line emission from the downward-moving hydrogen. In the solar case such red shifts have been difficult to observe, and one reason may be the turbulence caused by the high energy flux. Where the beam is more diffuse, the red shift should be more prominent.
2. Gamma ray emission is anticipated from a large stellar flare. A detector of 2500 cm^2 sensitive area operating in the 1-10 MeV range close to the capability of the Gamma Ray Observatory is on the threshold of detecting a flare, at d=5pc, 10^4 times the intensity of the larger flares seen by SMM. This assumes the detectability is photon limited, which is reasonable if the time and position of the flare are known from observations at other wavelengths.
3. Hard X-ray production is a consequence of the topology of the magnetic field, which in the Sun serves to produce high *energy flares*. Where active regions are diffuse, high concentrations of energy flux will not occur and hard X-ray emission will be inhibited. We predict that only rarely will dMe star flares be observed where the ratio of hard/soft X-rays is as high as in a "typical" solar flare.
4. Microwave radio bursts, which are associated with the production of hard X-rays, should also be largely absent in dMe stars. In the Sun the microwave burst (which is mainly incoherent gyrosynchrotron radiation) comes from electrons which escape from the X-ray-emitting region; this is why microwave bursts are invariably delayed with respect to hard X-rays. Other microwave bursts which are strongly polarized probably come from maser action, and it is not appropriate for us to comment on these.
5. Henoux *et al.*, (1988) have suggested that polarization of Hα radiation should be produced by low-energy proton bombardment. Discovery of polarization in stellar flares would be an important achievement.

6. References

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