FLARES AND CORONAL HEATING

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1. Introduction

The problem of the heating mechanism for the solar corona finds its origin in the realization, based on Doppler widths of optical emission lines (Edlen 1942), that its electron kinetic temperature is of the order of $1 - 4 \times 10^6$ K. Since the radiation temperature of the underlying photosphere is $\sim 6000$ K, radiative heating cannot be the source of the high temperatures. The earliest attempts to explain the anomaly were entirely in terms of shock heating, whose ultimate source was the photospheric and sub-photospheric convective motions. A review of the problem in 1961 by E. N. Parker (1963) listed those ideas which were in the forefront of peoples’ minds at that time. These were, without exception, based on some form or other of mechanical heating.

Space-borne instruments, especially X-ray imaging telescopes flown during the 1970’s, revealed that the modes of energy transfer involved in coronal heating were intimately related to the magnetic fields which permeate the corona. At about the same time X-ray satellites surveyed the stellar scene and discovered that coronae were a widespread phenomenon. Furthermore the distribution of stellar coronae on the HR diagram was not that predicted by the mechanical heating theories. Instead the occurrence of stellar coronae is at its maximum in the late-type dwarfs. This is pre-
ciscely the region of the HR diagram where dynamo generation of magnetic fields should be most efficient (see e.g. Golub 1983 and refs. therein).

Late-type dwarf stars also exhibit a range of phenomena collectively called "chromospheric activity". These include evidence of large-scale spots analogous to sunspots, frequent optical flares analogous to solar flares and strong emission lines in their optical spectra indicative of the presence of heated outer atmospheres. On a solar model for these phenomena, they would indicate the presence on the surfaces of these stars of concentrations of strong magnetic fields.

During IAU Coll. No. 71 in Catania in 1982, Dr. Dermott Mullan raised a question asking whether flaring and coronal heating might be related in a direct and intimate way. The predominant opinion in the subsequent discussion appeared to be that flaring and coronal heating were separate aspects of a wide spectrum of magnetic activity. Since there is a considerable interest in stellar chromospheric activity and stellar flares in particular at Armagh Observatory, we undertook a programme of observation, one of whose objectives was to evaluate this possibility. It is my intention here to try to summarize the current situation on this question as I see it.

2. Solar Flares and the Solar Corona

Solar flares, which are the basis of our models of stellar flares, are a complex phenomenon and there is as yet no detailed description of the physical processes involved with which everybody will agree. Nevertheless, certain details are becoming increasingly clear. Many flares occur within complexes of magnetic fields called active regions. Most will agree that a flare occurs when an instability develops in one or more magnetic loops which requires the magnetic configuration to rearrange itself. As a by-product of this rearrangement, magnetic energy is released. This energy may either produce local heating in the vicinity of the instability or, as seems more likely on the basis of recent evidence (Woodgate et al. 1983, Doyle et al. 1985), it may accelerate a beam of non-thermal electrons. The beam of electrons in such circumstances would be constrained to move parallel to the magnetic lines of force i.e. along the axis of the magnetic loop. The density of matter in the corona, where the bulk of the loop exists, is sufficiently low for the beam to travel relatively unimpeded. On reaching the chromosphere at the base of the loop the density rises steeply and the beam of electrons undergoes collisional braking. In the process a substantial part of the energy of the beam may be dissipated as heat. As a result, the former chromospheric material is heated to coronal temperatures and expands rapidly to fill the entire loop. Here it cools on a timescale of tens of minutes by radiating in the soft X-ray part of the spectrum (Figure 1).

The imaging soft X-ray telescope on board the SKYLAB orbiting platform revolutionized our impression of the solar corona. Instead of the quasi-uniform, amorphous structure seen as visible wavelengths, the X-ray images revealed that within the corona there are many hot, bright loop-like structures (see Figure 1, Culhane 1981). These are identical in appearance to the late stages of a solar flare. The question then naturally arises whether some or all of these loops consist of cooling flare plasma and what their contribution to the overall energy budget may be. In this
context, we should be clear that by the solar corona we mean the 3 – 4 million degree or more plasma which dominates the soft X-ray appearance of the Sun. If flaring contributes significantly to coronal heating then regarding a stellar corona as a static structure whose properties and behaviour are well described in terms of global mean parameters may lead to serious misconceptions.
Figure 2. (a) X-ray light curves of impulsive events observed by Lin et al. (b) Energy spectra of the events in 2(a). (Reproduced from Astrophys. J.).
An example of what I mean is the now largely abandoned acoustic theory of heating the solar corona. In this theory, the primary heating mechanism for the solar (and by implication the stellar) corona was the generation at photospheric or low chromospheric level of acoustic waves arising from sub-photospheric convective motions. Such a mechanism gives a quasi-continuous heating of the corona distributed in a uniform manner over the whole solar surface. This kind of approach to the problem of heating the corona must have been influenced by the visual impression of an almost uniformly distributed structure. The acoustic heating theory in its original form would have led to avoidance of active regions, within which convection would be magnetically inhibited, rather than the observed concentration of heating in active regions as observed in X-rays.

![Graph](image)

**Figure 3.** Frequency spectrum of Lin et al's events compared to that for larger flares (Reproduced from *Astrophys. J*).
3. Solar microflares and solar coronal heating

Recent solar data may throw some light on the relationship between flares and solar coronal heating. Lin et al. (1984) flew large-area X-ray detectors, sensitive in the energy range 13 – 600 keV, on a balloon-borne platform which observed the Sun for a total of 140 minutes in 1980, near solar maximum. During this time they recorded 25 impulsive hard X-ray events. They were typically of duration 20 seconds or less and the longest showed significant structure on timescales down to about 1 second (Figure 2a). Simultaneous observations at energies in the 5 – 6 keV range were provided by the ISEE-3 satellite. Most of the hard X-ray events corresponded to soft X-ray enhancements whose rise times coincided with the time of the hard X-ray burst. The soft X-ray events reached their peak at a later time, however, and decayed on a longer timescale (typically 3 – 4 minutes). Several of the hard X-ray bursts were found to coincide in time with Hα brightenings too small to be described as flares on the basis of the optical record alone. Three of the bursts had accompanying microwave type III bursts. In short these impulsive events appear to have most of the characteristics of larger flares differing from them only in total energy.

Lin et al.'s apparatus permitted a good determination of the energy spectrum of the four largest bursts. They show some degree of uniformity, all being power-law spectra with indices in the region -4 to -6 (Figure 2b). Employing these and the thick target model of Brown (1971) it is possible to derive an estimate of the energy in the primary electron beam giving rise to each of the four events. Then assuming that all of the events had similar spectra leads to a time-averaged injection of energy in the form of electrons of energy $\gtrsim$ 20 keV of $\sim 10^{24}$ erg s$^{-1}$. There is no evidence for a break in the spectrum at 20 keV however. If the power law extends down as far as 5 keV the energy injected into the corona must be revised upward to $\sim 10^{26}$ erg s$^{-1}$. There is a further consideration however. The rate of occurrence of these bursts as a function of energy is also a power law down to the smallest detected (Figure 3). If the spectrum continues in this manner to lower energies then the total rate of injecting energy into the corona must exceed the $\sim 10^{27}$ erg s$^{-1}$ needed to heat the active solar corona. If that is the case then the corona of the Sun may be directly heated by the energy injected by flare events.

4. Stellar Coronae

Stellar coronal observations cannot of course directly resolve structural detail. Rotation does offer the possibility of crude longitudinal resolution however. Optical starspots (analogous to sunspots) have been investigated in this way. X-ray observations of stars over several consecutive days are difficult to obtain, however, since satellite time is at a premium. In the few cases where a sufficient amount of data exists, variability is dominated by flare-like events which mask any time-averaged variation (see Golub 1983). As a result of this observational limitation, our knowledge of the coronae of flare stars and other closely related stars derive from small numbers of scattered observations. Therefore, most of the discussion of stellar coronal emission is in terms of mean X-ray luminosity $[L_X]$, the mean having been formed over one, two, or three periods of observation between which and within which there is a very large scatter.
Figure 4. Correlation between mean X-ray luminosity, $[L_X]$, and time-averaged luminosity in U-band flare light, $[L^*_u]$. (Reproduced from Doyle and Butler 1985).

4.1 Energetics of flaring vs coronal heating

Doyle and Butler (1985) have recently drawn attention to a striking correlation between these mean X-ray luminosities, $[L_X]$, and the mean luminosity in optical flare light, $[L^*_u]$ (Figure 4). Both of the quantities plotted here are somewhat uncertain since they are dependent on the total time for which data has been accumulated. Of the two, $[L^*_u]$ is much better determined for the majority of cases. It is very remarkable that the relationship is linear with a slope very close to 1 over more than 3 orders of magnitude in both quantities. Figure 4 suggests that the energy released in optical light by flares is linearly correlated with the mean level of coronal X-ray emission. The best fit straight line in the figure yields

$$[L_X] = 13.2 [L^*_u].$$

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This result strongly suggests that there is at very least a common underlying mechanism between flares and coronal heating in flare stars. In view of the speculations outlined above, it may also point to flares being the source of the multi-million degree coronal plasma.

If this latter possibility is to be defended, we must examine the energetics of flaring vis-à-vis the radiative energy lost in coronal X-ray emission. Here there are immediate problems. The quantity \( \left[ L_U^* \right] \) is the time-averaged optical energy radiated in the Johnson U-band alone. The colours of flare light suggest that the continuum emission of the most powerful optical flares continues to rise into at least the near UV (see e.g. Byrne 1983). Unfortunately, simultaneous optical and UV observations of stellar flares are still rather sparse and of relatively poor quality. It is clear from both optical photometry and UV spectroscopy that flares differ widely from one another. Nevertheless, analysis of a large sample of optical flares by Lacy, Moffett and Evans (1974) suggests that \( \left[ L_{UBV}^* \right] \approx 2.4 \left[ L_U^* \right] \) where \( \left[ L_{UBV}^* \right] \) is the time-averaged flare energy over the optical UBV bands. Allowing for the region of the optical not covered by these bands, we can safely conclude that \( \left[ L_{opt}^* \right] \) is greater than 3 \( \left[ L_U^* \right] \).

Our knowledge of the mean time-averaged UV flare energy is much less certain. It appears, however, from the data to hand that \( \left[ L_{UV}^* \right] \gg \left[ L_{opt}^* \right] \). From a consideration of the fact that only one hemisphere of the star may be observed at a time

![Figure 5. EINSTEIN X-ray observations of Prox Cen (Reproduced from Haisch et al. 1983).](image-url)
only half the total number of flares are recorded. Therefore

\[ [L_{UV \text{ and opt}}^*] > 12 [L_x^*]. \]

Thus it would appear that

\[ [L_{UV \text{ and opt}}^*] \approx [L_x]. \]

We must stress that there are uncertainties involved in our knowledge of both sides of this equation and that we have very little knowledge as yet of the contribution to the energy balance from the radio region of the spectrum (Gibson 1983) and none whatsoever concerning mechanical energy. Indeed in some solar flares the energy of mass motions may exceed that radiated by a considerable factor (Cranfield et al. 1980, Webb et al. 1980). Thus, there seems to be no objection on energetic grounds to the hypothesis that flares supply the energy for the X-ray corona.

4.2 Stellar X-ray microflares and coronal heating

There is, however, more direct evidence for the effect of flare-like events on the “quiet” coronal emission from active late-type dwarfs. Several authors have remarked that the X-ray emission from flare stars shows variability on short time scales. Haisch et al. (1983), using data gathered with the \textit{Einstein} satellite, commented on the variability of the flare star Proxima Centauri both on a timescale \( \approx 100 \) sec and over two observations taken more than a year apart (Figure 5). Golub (1983) similarly reported variations in X-ray output from BY Dra and CR Dra on time scales \( \approx 1000 \) sec. Examination of Figure 5 illustrates that the “fast” variation of the “quiescent” X-ray flux is on timescales \( < 100 \) sec and reaches a factor of \( 2-3 \) at least. In short, even when we observe the nominally “quiescent” coronae of the most active stars we have evidence of continuous variability or flare-like behaviour.

Optical flares on the latest type M dwarfs, such as Prox Cen, bear a striking resemblance to the solar impulsive X-ray events reported by Lin et al. (1984) (Figure 6). Their “spike” phases can be as short as a few seconds in total duration. Furthermore, these types of flare events can occur very frequently in the latest type stars such as Prox Cen. Walker (1981) has shown that Prox Cen flares in the optical at least once every 40 minutes. The optical energy of these flares is typically \( 10^{27} - 10^{28} \) ergs. In the absence of simultaneous X-ray and optical coverage, however, the identity of optical spike flares and the X-ray impulsive events described here must remain speculative.

There is another observation in the optical which resembles the X-ray variability reported by Haisch et al. (1983) and Golub (1983). It has long been noted by optical observers that the active dMe or “flare” stars exhibit instability in their \( U \) (optical ultraviolet)-band light. When attempts are made to define their mean (U-B) colours, these are found to be more scattered than those of less active stars of approximately the same spectral type. Furthermore, there is no evidence of a break in the energy spectrum of optical flares as a function of energy (Figure 7), the smaller amplitude flares becoming more frequent. Thus, the instability of the mean U-band light in dMe stars has been widely attributed to frequent small optical flares (Byrne 1979, Doyle, Byrne, and Butler 1986). Such small flares are frequent enough to be
Figure 6. A fast optical flare on Prox Cen (Byrne, unpublished). Each point corresponds to a 5 sec integration.

Figure 7. Cumulative frequency diagram of optical U-Band flares on the star Gliese 867B (Reproduced from Byrne and McFarland 1980).
identified with the X-ray variability discussed here. There must remain uncertainty of their identity until good quality simultaneous X-ray and optical coverage is achieved.

5. Conclusion

There appears to be an increasing body of evidence, from both solar and stellar observations made in X-rays in particular, that flares play a direct role in coronal heating. The evidence is not yet conclusive, but it is sufficiently strong to warrant closer examination, both observationally and theoretically. The ability to carry out these investigations is either available now or will be available in the near future.

References

Golub, L. 1983. ibid., p. 83.

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