VARIABILITY OF SOLAR AND STELLAR CORONAE

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ABSTRACT: Time variability of coronal emission from the Sun and other late-type stars is reviewed. The solar data are used as a guideline in interpreting the spatially unresolved stellar observations. Numerical simulations of solar and stellar flares are discussed with emphasis on recent applications to flares on M dwarf stars. The possible role of microflares in heating stellar coronae is also discussed.

1. Solar X-ray variability

1.1. Spatially-resolved observations

The Sun, as the nearest star to us, is the only one for which we can obtain spatially-resolved observations of its coronal emission. Since the solar corona has a temperature of \( \sim 10^6 \) K, it is best observed in line or continuum emissions at XUV and X-ray wavelengths. In the past decades, the Sun has been observed intensively in these wavelengths with high spatial resolution by various space-borne instruments, notably those on *Skylab*, the Solar Maximum Mission (*SMM*) and the recently launched *Yoh-koh* satellite. These observations have revealed that the solar corona is highly inhomogeneous and time variable (see reviews by Withbroe and Noyes 1977, Vaiana and Rosner 1978, Kundu and Woodgate 1986).

As an example, Fig. 1 compares *Skylab* XUV spectroheliograms of the Sun in the lines of Fe XV at 285 Å (\( T \sim 2 \times 10^6 \) K), Mg IX at 368 Å (\( T \sim 10^6 \) K) and Ne VII at 465 Å (\( 5 \times 10^5 \) K). A photospheric magnetogram is also shown for comparison (Sheeley et al. 1975). It is clear from the figure that coronal emission in the Fe XV line is concentrated primarily in loop structures. These loops not only contribute to the bulk of the emission in individual active regions, where the magnetic fields are more intense, but also inter-connect different active regions across the solar disk. The Sun as seen in lower temperature lines such as Ne VII and Mg IX shows finer structures than in Fe XV. In addition to active region loops, there is a network emission over the entire solar disk, as can be seen in the transition region line of Ne VII. This network emission is an extension to higher heights of the chromospheric network seen most prominently in the Ca II K line. These spectroheliograms demonstrate that coronal loop structures, though dominated by plasma at temperatures around \( 2 \times 10^6 \) K, receive a significant contribution also from material at lower temperatures.
Fig. 2 shows X-ray images taken over a period of several solar rotations by the AS&E X-ray telescope on Skylab. The dark regions are coronal holes, while the brightest areas are active regions. Scattered over the disk are many isolated X-ray bright points, which are related to rapidly evolving bipolar magnetic regions (Harvey, Harvey and Martin 1975, Golub, Krieger and Vaiana 1976). The richness of solar coronal structures and its time variability is apparent from time sequences of XUV and X-ray images. A vivid impression of this variability in spatially-resolved X-ray images of the Sun is provided by the photographic atlas of the Sun of Zombeck et al. (1978), which used data from the AS&E soft X-ray telescope on board Skylab.

Examination of time sequences of XUV spectroheliograms and X-ray images such as those of Figs. 1 and 2 shows that the solar corona changes over many time scales, from minutes to hours, days and weeks. The rapid, larger amplitude changes are due to flares, which may last from several minutes to a few hours. Significant changes also occur in quiescent coronal loops observed in X-rays (Haisch et al. 1988). As shown by XUV spectroheliograms taken a few minutes apart in the lines of Fe XV, Mg IX and Ne VII, individual loops may appear or disappear in minutes, especially those seen in Ne VII. Higher temperature loops (seen in Fe XV and X-rays) are more diffuse and evolve more slowly, remaining in a quasi-equilibrium state for tens of minutes (cf. Webb 1981). Over time scales of days the brightness of active region structures changes significantly, as shown by the X-ray images in Fig. 2. Brightness variations at UV wavelengths, which originate in the chromosphere and the transition region, have also been observed in the quiet Sun and in active regions (Cheng 1991).

1.2. Full-disk data

In X-rays the Sun has been observed continuously as a star for nearly three decades. Satellites of the Solrad and GOES series have recorded the integrated emission of the Sun in various soft X-ray bands (0.5-3 Å, 1-8 Å, 8-20 Å, 44-60 Å). Cross-calibration of different detectors has allowed the long term variations of the Sun to be monitored over the last three activity cycles (Kreplin 1970, Kreplin et al. 1977, Wagner 1988).

A simple inspection of some recent issues of Solar Geophysical Data will show daily plots of solar X-ray emission over the spectral bands 0.5-4 Å and 1-8 Å recorded by one of the geostationary satellites of the GOES series (Fig. 3). The integrated flux (averaged over 5 min intervals) appears to vary in a virtually continuous way, with amplitudes that range from the smallest detectable variations (a few tens percents) to two or three orders of magnitude. Most of this variability is due to flares (over time scales from several minutes to a few hours), but some of the more subtle variations are also due to changes in individual active region loops of the type reported by Haisch et al. (1988). Although prominent in soft X-rays, these variations are negligible when compared to the bolometric luminosity of the Sun. In the 1-8 Å band the X-ray flux is typically at the level of \( \sim 10^{-6} \) watt m\(^{-2}\), while the Solar Constant is 1367 watt m\(^{-2}\). Hence, soft X-ray emission in this passband contributes only \( \sim 10^{-9} \) of the solar luminosity. In spite of this, the X-ray variations are quite conspicuous, and may reach several orders of magnitudes in a large
Figure 1. XUV spectroheliograms of the Sun in the lines of Fe XV, Ne VII and Mg IX, obtained by the NRL XUV Spectroheliograph on Skylab. A photospheric magnetogram is shown for comparison in the bottom right panel (from Sheeley et al. 1975).
Figure 2. X-ray images of the Sun covering several solar rotations obtained by the AS&E soft X-ray telescope on Skylab (courtesy of AS&E).

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solar flare. As a rule, the amplitude of the variability is larger in the harder spectral bands.

![Figure 3](image.png)

**Figure 3.** Two-days of continuous monitoring of the full-disk Sun in the spectral bands 0.5-4 Å and 1-8 Å obtained by the **GOES 7** satellite (from **Solar Geophysical Data**).

In addition to short term variability, the full-disk X-ray flux changes on longer time scales, that are associated with the rotation of the Sun, the birth and decay of individual active regions and the 11-year activity cycle. We know this because we can relate directly the variations observed in the spatially integrated solar X-ray flux to the spatial distribution of such emission as revealed by high-resolution X-ray images. Obviously, this link can be made only in the case of the Sun and this is the reason why solar observations are of such paramount importance for interpreting time variations observed in spatially unresolved stellar observations.

Zombeck et al. (1978) compared the spatially resolved X-ray images of the Sun obtained during the **Skylab** mission with the 8-20 Å flux obtained over the same period by the **Solrad 9** satellite. Some interesting considerations can be made. First, the integrated 8-20 Å flux (obtained by making daily averages and subtracting the contribution of flares) shows a well-defined modulation with a period of slightly less than a month, that is clearly due to the solar rotation. The amplitude of the modulation in the 8-20 Å passband is quite large (typically a factor ~ 10), but varies from cycle to cycle; also the general shape of the light curve varies from one rotation to the next, but in all cases the X-ray daily flux follows quite strictly other activity indices, such as the sunspot number, the Ca II plage index and the 10.7 cm radio flux (Fig. 4). The modulation is caused by the non-uniform distribution of active regions across the solar surface, while the different amplitudes and shapes from one cycle to the next are caused by the intrinsic variations in the number, extension and intensity of the active regions, which grow and decay on time scales that are comparable to a few solar rotations or less.
Figure 4. Full-disk 8-20 Å flux of the Sun (bottom panel) and various solar activity indices during the Skylab mission. The X-ray flux, measured by the Solrad 9 satellite, is given in units of $10^{-4}$ erg cm$^{-2}$ s$^{-1}$. Activity indices include (from top to bottom): sunspot number, number of X-ray flares, Ca II plage index and radio flux at 10.7 cm (from Zombeck et al. 1978).
There are also large variations of the average full-disk X-ray flux throughout the solar cycle. Wagner (1988) used the 1-8 Å GOES data to estimate the variations throughout the cycle of the background X-ray flux (i.e. the flux due principally to active regions, with the contribution of flares and coronal mass ejections subtracted). He found that the annually smoothed daily background 1-8 Å flux varied by at least a factor 85 from the solar minimum in May 1975 to the solar maximum in September 1981 and back again to the minimum in October 1986 (Fig. 5). Similar results were obtained previously for softer X-ray spectral bands observed with the Solrad satellites. For instance, Kreplin (1970) estimated that from the minimum in 1964 to the maximum in 1969 the 8-20 Å flux varied by a factor ~ 200, and the 44-60 Å flux varied by a factor ~ 20. These results show that the amplitude of the variation due to the activity cycle is quite large in the solar case, typically as large as a factor ~ 100 in the spectral bands 1-8 and 8-20 Å, and a factor ~ 10 in the band 44-60 Å. The X-ray cycle determined in this way is well correlated with the sunspot number and especially with the white-light facular area (Wagner 1988). Again, this indicates that coronal emission is controlled by the photospheric magnetic field.

Figure 5. Variation of the annually smoothed 1-8 Å daily background flux during Solar Cycle 21. The daily background flux represents the quiescent X-ray flux from active regions, with little contribution from flares and coronal mass ejections (from Wagner 1988).
2. Stellar X-ray variability

2.1. Irregular variability

In comparison with the solar case, our knowledge of stellar X-ray variability is extremely limited. In spite of the great progress made over the past decade in the understanding of stellar coronal emission (see reviews by Rosner, Golub and Vaiana 1985, Pallavicini 1988, 1989), we now little of the time behaviour of coronal sources, except for a few specific classes of objects such as RS CVn binaries and dMe flare stars. We know (Collura et al. 1989) that at least some early-type stars are variable on time scales of hours to days (and possibly even minutes). However, the physical reasons for this variability are still poorly understood and early-type stars will be excluded from the rest of this paper. We also know very little about long-term variability that could be produced by activity cycles in late-type stars: the time coverage is too limited, and the contamination by short-term variability too large, to allow a reliable determination of X-ray stellar cycles, at least for the time being. Extreme variability is present in pre-main sequence objects and this variability is commonly interpreted as originating from magnetic processes similar to those operating in other late-type stars (Walter and Kuhi 1984, Montmerle 1985, Feigelson 1987, Gahm 1988, 1989, Montmerle et al. 1992). It is unclear whether the variability of PMS objects originates entirely from flares or, more likely, is a combination of flaring and non-flaring activity.

A detailed investigation of time variability of coronal sources observed with *Einstein* has been carried out by Ambruster, Sciortino and Golub (1987) who analyzed a sample of 19 late-type stars (mostly flare stars) using an optimized $\chi^2$ test. They found that short-term variability (on time scales from several minutes to hours) was common to the stars in the sample, with typical amplitudes of $\sim 30-50\%$. A problem with the data analyzed by Ambruster et al. is the presence of large data gaps due to the low orbit of the *Einstein* Observatory (Fig. 6). Such gaps make it difficult to determine the physical nature of the observed variability and to distinguish between slowly evolving flares (on time scales of a few hours) and the repeated occurrence of shorter lived events (tens of minutes) overimposed on a more constant quiescent background.

The *EXOSAT* satellite which permitted continuous coverage of a source for up to three days, represents a significant improvement in this respect, allowing a better separation between flaring and quiescent emission. As an example, we show in Fig. 7 a 24 hours continuous observation of the multiple system Castor A, B and C (the latter component is the eclipsing binary flare star YY Gem) made with the LE and ME instruments of *EXOSAT*. Pallavicini, Tagliaferri and Stella (1990) have analyzed the entire sample of dMe flare stars observed by *EXOSAT* (25 sources for a total monitoring time of nearly 300 hours). Their study has confirmed the high degree of variability of the quiescent emission of late-type stars and has provided a clear picture of flaring activity on these stars. In addition, comparison of different *EXOSAT* pointings of the same source, and with previous *Einstein* observations, has also given some information on long-term variability (on time scales of months to years).
Figure 6. Variability analysis (top) of an *Einstein* observation (bottom) of the flare star UV Ceti. The three curves in the top panels represent probabilities of 90%, 99% and 99.9% that the source is variable. Note the large data gaps in the light curve (from Ambruster, Sciortino and Golub 1987).

Several important results emerge from the available data. First, the short-term variability is highly erratic, as is the case for the solar X-ray variability on time scales from minutes to days. This suggests that in analogy with the solar case the short-term variability of late-type stars is largely due to magnetic processes that occur in the coronae of these stars. These processes include both flares and more gradual variations, probably associated with the emergence of new magnetic flux and/or to fluctuations of the heating rate in individual active region structures. Secondly, the amplitude of the long-term variations of the stellar quiescent X-ray emission appears to be small (a factor 2 or 3 at most). This is much less than could be predicted from the solar case. Even taking into account the rather soft passbands in which *Einstein* and *EXOSAT* observations have been made, it is somewhat surprising that we do not observe –outside flares– variations as large as a factor 10 to 100, as have been detected for the Sun by the *Soledad* and *GOES* satellites. A likely explanation is the predominance among the stellar X-ray sources detected so far of active stars which emit at levels much larger than the solar corona. These
stars should be much more covered by active regions than the Sun, thus causing a drastic reduction of the X-ray variability due to the rotational modulation and the activity cycle. Moreover, only the largest flares can be detected in intrinsically brighter X-ray stars:

![Graph showing EXOSAT observations of flares](image)

**Figure 7.** A long (24 hours) continuous EXOSAT observation of the eclipsing binary flare star YY Gem (Castor C) and of the A-type visual binary Castor A+B. Flares are observed in the EXOSAT LE from both Castor A+B and YY Gem, while the two sources are not resolved by the ME (from Pallavicini et al. 1990).

### 2.2. Phase-dependent variations

Phase-dependent variations due either to the rotation of an individual star or to eclipses of one star by the other in eclipsing binary systems can be used to infer the spatial structure of stellar coronae. There have been several attempts in the literature to determine the rotational modulation of stellar coronal emission. In most cases the results have been inconclusive, owing to the superposition of flaring and non-flaring variability and/or the lack of observations extending over more than one rotation period (e.g. Collier Cameron et al. 1988, Agrawal 1988, Agrawal and Vaidya 1988; see also Pollock et al. 1991 for a different interpretation of Agrawal's results). Recently, the ROSAT All-Sky Survey has provided a new method for detecting rotational modulation at X-ray wavelengths. Since the Survey data consist of snapshots (typically ~ 20 sec long) regularly spaced at intervals of 96 min,
for periods of two days or longer, we can derive complete light curves for bright sources whose rotational periods are of the order of a few days or less. A systematic analysis of the ROSAT All-Sky Survey data in search of rotational modulation is expected to provide important insights into the spatial distribution of X-ray emitting structures and the fraction of the star covered by active regions.

Eclipsing binary systems provide the best opportunity to infer the spatial distribution of hot coronal material around stars. The changes that are produced in the light curve as one star passes in front of the other permit, at least in principle, to determine the location, fractional area and height of the bright emitting structures. Unfortunately, the solution is often not unique and there are large ambiguities in the interpretation of the light curve.

Several eclipsing binary systems have been observed using instruments on board Einstein, EXOSAT and ROSAT. These include Algol, the RS CVn systems AR Lac, TY Pyx and ER Vul, and the dMe flare star YY Gem (Walter, Gibson and Basri 1983, White et al. 1986, 1987, 1990, Culhane et al. 1990, Schmitt 1992). Being the closest and brightest eclipsing binary among RS CVn stars, AR Lac has a special importance and has been observed for eclipses by all three satellites.

Complete coverage of one orbital period of AR Lac was obtained by White et al. (1990) using both the Low Energy (LE) detector (sensitive to the spectral band 0.04 - 2 keV) and the Medium Energy (ME) detector (1 - 6 keV) on board EXOSAT. The primary eclipse was observed by both detectors, but there was no obvious eclipse in the ME data. This indicates that there is a high-temperature component sufficiently extended to avoid eclipses by the two stars, while at the same time compact structures must also exist close to the surface of at least one of the components. Similar results were obtained from an EXOSAT observation of the eclipsing binary TY Pyx (Culhane et al. 1990).

White et al. (1990) have carried out extensive model simulations of the EXOSAT LE light curve of AR Lac, using both $\chi^2$ fitting and maximum entropy techniques. While the absence of a deep eclipse in the ME data clearly indicates that high-temperature plasma (at $T \geq 10^7$ K), filling the entire space between the stars, must exist, there are large ambiguities with regard to the location and extent of the X-ray bright regions on the two stars. Acceptable solutions are obtained both by locating the emitting structures on each of the two components, or by assuming that only one of the two stars is X-ray bright. There are also large uncertainties with regard to the height of the various structures.

New observations of AR Lac obtained recently by ROSAT are discussed by Schmitt elsewhere in this volume. The ROSAT PSPC has observed AR Lac both in the Full-Sky Survey and in the pointed mode. The primary eclipse was seen in all cases, with only marginal evidence of a shallow dip preceding secondary eclipse. This is consistent with previous Einstein and EXOSAT results. However, in contrast with EXOSAT, the primary eclipse was seen in all ROSAT X-ray energy bands, including the hardest one (1.1-2.4 keV). Spectral analysis of the PSPC data indicates that the major contribution to the ROSAT hard band comes from plasma that is virtually at the same temperature as that contributing to the EXOSAT ME band (where the eclipse was not seen). This could indicate either that the eclipse was too shallow to be detectable in the less sensitive EXOSAT ME data or that the structure of the corona has substantially changed between the two observations.

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3. Solar and stellar flares

3.1. Numerical simulations of flares

So far, flares have been the most commonly observed and best understood form of variability in late-type stars. A large variety of X-ray flares have been observed from M dwarf flare stars, from RS CVn and Algol-type binaries and from pre-main sequence objects (Kahler et al. 1982, Haisch et al. 1983, de Jager et al. 1986, 1989, Doyle et al. 1988a, b, White et al. 1986, 1990, Tagliaferri et al. 1988, Tsuru et al. 1989, Pallavicini, Tagliaferri and Stella 1990). A flare has also been observed from the A-type visual binary Castor (Pallavicini et al. 1990), although in this case it is not yet clear whether the emission originated in one of the A-type primaries of the system (both spectroscopic binaries), or in an unseen late-type companion. Surprisingly, there is only one reported case of an X-ray flare from a "normal" solar-type star (the G0 dwarf π¹ UMa; Landini et al. 1986). This was most likely due to insufficient time devoted so far to the X-ray monitoring of "normal" solar-type stars.

As shown by extensive analysis of Einstein and EXOSAT data (see reviews by Haisch 1983, Linsky 1991, Pallavicini 1992), the light curves, time scales and flare temperatures are all similar to those typically observed in solar flares, but the released energies are orders of magnitude larger. The average temperatures are usually in the range $2 - 4 \times 10^7$ K, though higher temperatures have been reported for some flares on RS CVn and Algol-type systems. The time scales range from several minutes to a few hours and there is some indication of the existence of different classes of stellar X-ray flares, similar to solar compact and 2-ribbon events (Pallavicini, Serio and Vaiana 1977, Poletto, Pallavicini and Kopp 1988). The total energies released in the X-ray passband range from $10^{30}$ to $10^{34}$ erg for flares on dMe stars, and from $10^{35}$ to $10^{36}$ erg for flares on RS CVn binaries and PMS objects. For comparison, the typical energies of solar X-ray flares (integrated over the X-ray band and throughout the flare lifetime) are $10^{28}$ to $10^{31}$ erg. The events observed on RS CVn binaries and PMS objects are usually more energetic and longer-lived than those observed on dMe stars (Montmerle et al. 1985, White et al. 1986, 1990, Tsuru et al. 1989, Tagliaferri et al. 1988, Pallavicini and Tagliaferri 1989, Culhane et al. 1990). We cannot exclude, however, that smaller and shorter-lived events also exist on these stars, but are missing due to the much higher quiescent emission.

The observations obtained so far show that at least for flares on M dwarfs there is a strong analogy between solar and stellar events, except for the much larger energies typically involved in the stellar case. It is expected therefore that models similar to those developed in the solar case should also be able to reproduce the observations of stellar flares. Great interest has arisen recently in the development of hydrodynamic models that treat the time dependent response of a coronal loop to various heating perturbations. Several numerical codes have been developed for solar flares (e.g. Nagai 1980, Cheng et al. 1983, 1985, Pallavicini et al. 1983, Nagai and Emslie 1984, MacNeice et al. 1984, Fisher et al. 1985 a, b, c; Peres et al. 1987). It is natural to extend similar calculations to the stellar case.
A first attempt to model a stellar X-ray flare by means of hydrocodes was made by Reale et al. (1988) who used the Palermo-Harvard one-dimensional single-fluid code to fit a long-duration event observed on Prox Cen by the \textit{Einstein} Observatory (Haisch et al. 1983). Cheng and Pallavicini (1991) have carried out extensive modelling of flares on dMe stars using the NRL one-dimensional two-fluid code. In all cases, intense heating was assumed to occur close to the top of the loop. Rather than trying to reproduce a particularly well observed event, they built a grid of 10 different models by changing loop length, preflare conditions, flare heating rate, and spatial and temporal dependence of the heating function.

By exploring the parameter space, it is thus possible to get better insights into the flare process, and to test how sensitive the models are to the assumed input parameters.

The basic hydrodynamic results are similar to those obtained by applying the same codes to the solar case (Pallavicini et al. 1983; Cheng et al. 1983, 1985; Peres et al. 1987). The major difference is due to the higher gravity and smaller pressure scale height of dMe stars. If energy is deposited at the loop top, a high temperature region forms there. Energy is rapidly conducted down towards the loop footpoints and the transition region between the chromosphere and the corona steepens and moves downwards. If the energy conducted to the chromosphere is larger than can be radiated away, a high pressure region forms at the top of the chromosphere. The heated chromospheric material expands upwards at velocities of several hundred Km s\(^{-1}\) filling the coronal portion of the loop ("chromospheric evaporation"), while at the same time the high pressure region acts like a piston compressing the underlying chromospheric material. However, because of the large gravity and small pressure scale height of dMe stars, the compression region encounters a very steep density gradient that limits the amplitude and time duration of the compressed region. For plausible energy input rates (i.e. those which appear to be required to fit the X-ray observations), it seems unlikely that the compressed region that forms in a thermal flare can contribute significantly to the flare optical emission in dMe stars.

The numerical results of Cheng and Pallavicini (1991) appear in good agreement with the general properties of X-ray flares observed by EXOSAT from M dwarf stars. Cheng and Pallavicini (1992) have also calculated detailed line profiles around the line complexes at 1.85 Å (Fe XXIV, XXV) and 3.2 Å (Ca XVIII, XIX), at different phases throughout the flare (Fig. 8). The simulations for their model 8 show that there are large blue shifts in the Fe XXV and Ca XIX line profiles during the initial heating phase (left-hand panel of the figure). At \(t = 23\) sec, the peak of the Fe XXV resonance line \((w)\) is blue-shifted by about 1.7 mÅ, which corresponds to an upflow velocity of about 300 km s\(^{-1}\). Near the flare maximum and in the flare decay phase, the blue-shifted component has disappeared. The right-hand panel of the figure shows the light curves of the resonance line \(w\) of Fe XXV and of the \(f\) line of Fe XXIV, and their intensity ratio, throughout the evolution of the flare. Since the \(j/w\) ratio decreases with increasing temperature, the figure shows that the flare temperature increased to a high value rapidly during the initial heating phase and remained high during the rise phase of the flare. The temperature decreased during the later cooling phase, as shown by the rapidly increasing ratio of \(j/w\). At flare maximum (at \(t = 322\) sec), the ratio \(j/w\) (which is a measure of the electron temperature) gives a peak temperature of the flare plasma of \(10^8\) K, in agreement with the results of the hydrodynamic calculations. When the Fe line profile is time-integrated for the duration of the flare rise phase (\(~70\) sec), a large blue-shifted component in the Fe XXV \(w\)-line can still be identified clearly. The predicted large blue shifts on the Fe XXV and Ca XIX profiles during the initial heating...
Figure 8. Time evolution of X-ray line profiles computed on the basis of the hydrodynamic stellar flare model of Cheng and Pallavicini (1991). (left panel) Line profiles of the Fe XXIV-XXV line complex at different flare phases; (right panel) light curves of the Fe XXV $w$ and of the Fe XXIV $j$ lines, and their ratio, throughout the evolution of the flare (from Cheng and Pallavicini 1992).
phase could possibly be observed by a Bragg crystal spectrometer with a resolving power greater than 800. Blue shifted components in the profiles of these lines have been observed in solar flares by crystal spectrometers on the P78-1 and SMM satellites (Doschek et al. 1980, Antonucci et al. 1982). Hopefully, similar blue-shifted components will be observed for stellar flares by the next generation of X-ray observatories, such as AXAF.

3.2. MICROFLARES AND CORONAL HEATING

Solar observations at a variety of different wavelengths have revealed that in addition to flares there are also less energetic shorter-lived events ("microflares") that occur randomly in space and time. On the Sun, hard X-ray microflares with energies of \( \sim 10^{27} \) ergs have been observed by Lin et al. (1984), and transient brightenings in UV have been reported by Porter et al. (1987). Parker (1988) has proposed that magnetic reconnection at tangential discontinuities (current sheets) caused by the continuous shuffling and intermixing of magnetic field lines anchored in the dense photospheric layers (Parker 1983 a,b) are responsible for coronal heating. These magnetic reconnections result in short-lived transient events called "nanoflares" (with typical energy of \( \sim 10^{24} \) erg). On active late-type stars with more powerful X-ray coronae we may expect that "microflares" and "nanoflares" may be substantially more energetic than those on the Sun (as stellar flares typically are). It may be interesting therefore to search for a signature of their presence in disk-integrated stellar observations.

Butler et al. (1986) have reported evidence of stellar microflares in EXOSAT observations of some dMe flare stars. By comparing the X-ray data (binned over time intervals of 30 and 60 sec) with optical observations in the H\(\gamma\) line, they noticed the simultaneous occurrence of many short-lived events at both wavelengths. From this, and other indirect evidences, they concluded that the quiescent X-ray emission of dMe stars, and possibly of all late-type stars, results from the continuous occurrence of "microflares" lasting from tens of seconds to several minutes and with characteristic energies of \( \sim 2 \times 10^{30} \) erg. This suggestion, though attractive, has raised some controversy, since the correlation between X-ray and optical events was far from being perfect, the binning of the X-ray data was too short to ensure a good statistics, and finally it was unclear whether these short-lived fluctuations occur continuously as claimed.

In order to check the above suggestion, Collura, Pasquini and Schmitt (1988) and Pallavicini, Tagliaferri and Stella (1990) have independently analyzed the EXOSAT data using a variety of statistical tests, including \( \chi^2 \) tests, autocorrelation techniques and power spectrum analysis. The conclusion was that there is no statistically significant evidence in the EXOSAT data for the presence of continuous short-term variability of the type suggested by Butler et al. Variability is present, but it occurs on longer time scales and larger energies than those suggested by Butler et al. for their "microflares" (see also similar conclusions by Ambruster, Sciortino and Golub 1987 based on Einstein data).

While detection of microflares in stellar observations has to wait for future data with higher sensitivity, it is of interest to simulate numerically the microflare heating process, using the available hydro-codes. Recently, several attempts have been made to simulate microflare heating in solar coronal loops (Raymond 1990, Kopp and Poletto 1991, Sterling et al. 1991).
To simulate properly microflare heating, the frequency distribution of microflares has to be considered. Extensive optical monitoring of flares from dMe stars has shown that the frequency distribution of flares vs. energy E obeys a power law of the form dN/dE \sim E^{-\beta} with \beta \sim 1.8 (Gershberg and Shakhovskaya 1983, Petterson, Coleman, and Evans 1984, Shakhovskaya 1989). A similar frequency distribution has also been obtained for solar flares, using observations at many different wavelengths (Hudson 1991). When extrapolated to energies less than 10^{26} ergs, the observed frequency distribution does not appear to have enough energy to meet the heating requirements of the solar corona (Hudson 1991, Petrosian 1991). To heat the solar corona by microflares, a much steeper flare energy distribution is required. Whether the same conclusion also applies to stars is still an open question that could be investigated profitably by means of numerical simulations.

References


