ENERGY RELEASE IN STELLAR FLARES

R. PALLAVICINI
Osservatorio Astrofisico di Arcetri
Florence, Italy

ABSTRACT. Flare-like events similar to those observed on the Sun occur on many different types of stars, particularly on late K and M dwarfs. Although the physical mechanisms responsible for these events remain largely unknown, it is likely that the flare energy derives from dissipation of magnetic fields as is the case for solar flares. We review the basic observational facts that suggest an analogy between solar and stellar flares and we discuss how the different physical conditions occurring on stars may affect the application of current solar-type models to the stellar case. We show that, in spite of a qualitative agreement found between model predictions and observations, there is still no convincing evidence that stellar flares are simply scaled-up versions of solar flares. Major advances in the observations of stellar flares are required before this fundamental question can be safely addressed.

1. Introduction

Over the past several years it has become increasingly evident that solar-type phenomena occur in a variety of different astrophysical contexts. In particular, stars of spectral type later than F show evidence for chromospheres, coronae, winds, magnetic fields and surface inhomogeneities such as spots, plages and flares. Since these stars are rotating magnetized gaseous bodies with a subphotospheric convective zone, it is generally accepted that some sort of dynamo action is at work, as believed to occur for the Sun. The dynamo-generated magnetic fields emerging at the stellar surface are thought to be responsible for the observed activity phenomena.

This paper will focus only on one particular form of activity, i. e. stellar flares, and will be further restricted to only one class of stars, the so-called UV Ceti-type flare stars. These are late K and M dwarfs in the solar neighbourhood that are known to be characterized by intense flaring activity at optical, XUV and radio wavelengths. The reason for selecting UV Ceti-type stars while discussing stellar flares in the context of a solar meeting is mainly dictated by the fact that flares from UV Ceti-type stars present the greatest analogy to solar flares, in contrast to the case of other stellar sources (e.g. RS CVn and Algol-type binaries and pre-main sequence objects) for which there are probably more differences than similarities with respect to the solar case (see, e.g., Mullan 1985, Pallavicini and Tagliaferri 1989, Byrne 1989).

There are, in fact, many analogies between solar flares and flares from UV Ceti-type stars, as has been most recently discussed at the Conference held in 1988 at Stanford University (IAU Coll. No. 104, see proceedings in Solar Physics Vol. 121, 1989 and in Haisch and Rodonò 1989). There are also significant differences, however, between solar and stellar flares. Hence the fundamental question arises: are these differences due to the different physical environments in which the same basic physical mechanisms occur, or rather are the environments so different that even the basic flare mechanisms may be different in the solar and stellar case?

1.1 Flare energetics

Before trying to answer the above question, one has to make a fundamental assumption, i. e. that the energy released in stellar flares derives from dissipation of magnetic fields as believed to occur for solar

E. R. Priest and V. Krishan (eds.), Basic Plasma Processes on the Sun, 77–92.

flares. There is no compelling evidence in the stellar case to believe that this is actually true (and, in fact, a variety of exotic, basically non-solar models were proposed in the past, cf. Gurzadyan 1980). However, in the absence of any other viable alternative, we shall assume that this is the case in spite of the fact that the observational evidence for this remains quite meager.

Under the assumption above, a substantial difference appears to exist between the solar and stellar case when considering the energetics of the flare phenomenon. The total radiative energy released in the largest solar flares is on the order of $\approx 10^{32}$ erg, while the total radiative energy released by large flares on M dwarf stars may be as high as $\approx 10^{35}$ - 10^{36} erg (cf. Gershberg 1989; note that these energies are lower limits, since the contribution of mass motions to the energy budget of stellar flares is unknown). If this energy has to come from dissipation of magnetic fields, the energy ΔE released by the flare must be related to the magnetic field strength B and to its variation ΔB by the simple relationship:

$$\Delta E = \frac{B\,(\Delta B)}{4\,\pi}\,V \qquad (1)$$

where V is the flare volume.

For the Sun, $\Delta E \approx 10^{32}$ erg and the typical volume for a large 2-ribbon flare is $V \approx 10^{29}$ cm^3 (see, e.g., Svestka 1976). Hence $B(\Delta B) \approx 10^4$. If $B \approx 300$ Gauss (a reasonable value for solar flares), a variation $\Delta B \approx 30$ Gauss is sufficient to account for the flare energy release. This is not so in the stellar case, for which $\Delta E \geq 10^{35}$ erg. In fact, if the volume were the same as in the solar case, $B(\Delta B)$ would be $\approx 10^{7}$, and in this case one should dissipate entirely a magnetic field of $\approx$3000 Gauss in order to do the job. More likely, if we want to maintain the same ratio 1:10 that we have assumed above for the solar case, one has to postulate magnetic fields as high as $\approx 10^4$ Gauss in M dwarfs and variations $\Delta B \approx 10^3$ Gauss. At present we cannot exclude that magnetic fields as high as 10^4 Gauss may exist on M dwarfs (cf. Mullan 1984) but, if so, this certainly is a rather non-solar situation.

Alternatively, the flare volume may be much larger than in the solar case. For instance, if the volume were one order of magnitude larger, say $\approx 10^{30}$ cm^3, $B(\Delta B) \approx 10^6$ and one needs to dissipate $\approx$300 Gauss in a field of $\approx$3000 Gauss. Note that a flare volume $V \approx 10^{30}$ cm^3 or larger implies that the flare linear size is comparable to the stellar radius in an M dwarf (since in these stars $R_* \leq 0.5\ R_o$); this is again a quite non-solar situation. In either case, it is hard to escape the conclusion that larger volumes or higher magnetic fields or both are required by stellar flares.

1.2 Flare diagnostics

Another important point to be kept in mind is that the primary energy release process is difficult to test observationally even in the case of the Sun (not to speak of stars). The available observational tests, therefore, refer almost exclusively to secondary processes and energy transport mechanisms. The relevant question is what kind of flare diagnostics are accessible in the case of stellar flares.

In the solar case, there is a wealth of observational diagnostics of flares, ranging from γ-rays to radio wavelengths and involving a variety of different spatial, spectral and temporal resolutions (see reviews in Sturrock 1980 and Kundu et al. 1989). This is not the case for stellar flares. There is one observational datum (optical continuum emission) that is probably better known for stellar than for solar flares (only recently systematic high-sensitivity observations of solar white-light flares have started to become available; cf. Neiding 1989). Other diagnostics (optical line emission, UV line and continuum emission, soft X-rays, radio emission) are also sufficiently well known for stellar flares. However, there is a large number of other diagnostics (e.g. hard X-rays, γ-rays, particle emission, mass ejections) that remain completely unaccessible in the stellar case, in addition to the fact that no spatial information is of course available. Our knowledge of magnetic fields and mass motions remain also extremely limited, if at all available. These fundamental observational limitations need to be taken into account when comparing solar and stellar flares and when trying to determine how successful solar models are in explaining stellar flares.

2. Observations

It would not be possible in the limits of a short review paper to summarize all observational data that have been collected in the past several years on stellar flares. Only a few observational results will be presented here with emphasis on the constraints that these data can put on stellar flare models. For a more comprehensive discussion of stellar flare observations and a complete list of references the reader is referred to a number of excellent conference proceedings such as Byrne and Rodonò (1983), Gondhalekar (1986), Havnes et al. (1988), Haisch and Rodonò (1989), Mirzoyan (1989).

In order to illustrate the main points with some specific examples, Figs. 1 and 2 show results of coordinated multi-wavelengths observations of stellar flares as published by Rodonò (1989) and Kahler et al. (1982), respectively. These are perhaps the best cases of stellar flares observed so far simultaneously at various frequencies. Fig.1 refers to a flare observed on 28 March 1984 from AD Leo: complete coverage was obtained at optical wavelengths (both photometry and spectroscopy) as well as at microwaves (2 cm and 6 cm). Infrared observations were also obtained in the K-band (2.2 μ), while UV observations were limited to the Mg II lines. Unfortunately, no X-ray observations could be obtained for this event. Fig. 2 shows a flare observed from YZ CMi on 25 Oct 1979. In addition to observations in optical continuum and Balmer lines, soft X-rays were observed, thus providing information also on the coronal portion of the flare. In the same event (Fig. 2) a decimetric burst was detected which was delayed by 17 minutes with respect to the optical continuum emission. Other relevant flare features which appear in Figs. 1 and 2 will be discussed later on.

2.1 Optical continuum emission

In contrast to the case of solar flares, stellar flares have been most extensively studied in broad-band optical continuum. Since stellar flares are a blue phenomenon while UV Ceti-type stars are intrinsically red, the flares are best seen in the U and B bands where the flare amplitude may be as high as five to six magnitudes (Byrne 1983, Pettersen 1988, 1989, Gershberg 1989, Shakhovskaya 1989). Statistical studies over a large number of flares (Lacy et al. 1976, Gershberg and Shakhovskaya 1983, Pettersen et al. 1984) indicate that the energy emitted in the U band is only slightly larger than in the B band ($E_U \approx 1.2\ E_B$) while the total energy released at optical wavelengths $E_{opt} \approx 3\text{-}5\ E_U$. The total bolometric luminosity of a stellar flare is estimated to be $E_{bol} \approx 6\ E_{opt} \approx 20\text{-}30\ E_U$. On the basis of these empirical relationships it is estimated that the total radiative energy released by flares on UV Ceti-type stars ranges from less than $\approx 10^{29}$ erg to more than $\approx 10^{35}$ erg. The intrinsically brighter stars flare more frequently than the intrinsically fainter stars and produce more energetic flares. While the latter result may be partially due to a selection effect, the higher flare frequency of intrinsically brighter stars suggests a dependence on the stellar radius, as might occur for instance if larger areas of the star are covered by active flaring regions. Although periodicities have occasionally been reported, there is no convincing evidence that stellar flares repeat regularly in time. Surprisingly enough, no periodicities related to the stellar rotation and/or to stellar cycles have yet been found. The available evidence suggests instead that stellar flares occur randomly in time.

The light curves of optical flares (see, e. g., Fig. 1a) present a large variety of different shapes with typically impulsive, often structured, profiles. The observed rise times are in the range ≈ 1-100 sec and the observed decay times are on the order of ≈ 10-1000 sec. The large flares tend to have longer time scales than small flares, as also observed for solar 2-ribbon flares. Moreover, flares observed in the optical continuum are typically more impulsive and of shorter duration than flares observed in optical Balmer lines or in soft X-rays. This is similar to what observed in solar flares, where white-light emission has a much shorter lifetime (and is localized in much smaller areas) than Hα emission. In solar flares there is a very good temporal correlation between white-light flares and hard X-ray emission. If the same were true for stellar flares, we could use the optical continuum emission as a proxy for hard X-rays (which are otherwise unobservable at the present sensitivity levels). Although there is no observational support for this claim, the solar analogy suggests that optical continuum emission could indeed be used to derive information on the primary energy release and particle acceleration in stellar flares.

An important observational finding recently reported by Rodonò (1989) is also illustrated in Fig. 1a. A "negative" flare is observed at IR wavelengths at the time of the optical continuum flare. There is so far no simple explanation for this effect, which is probably related to a change in opacity as a consequence of the

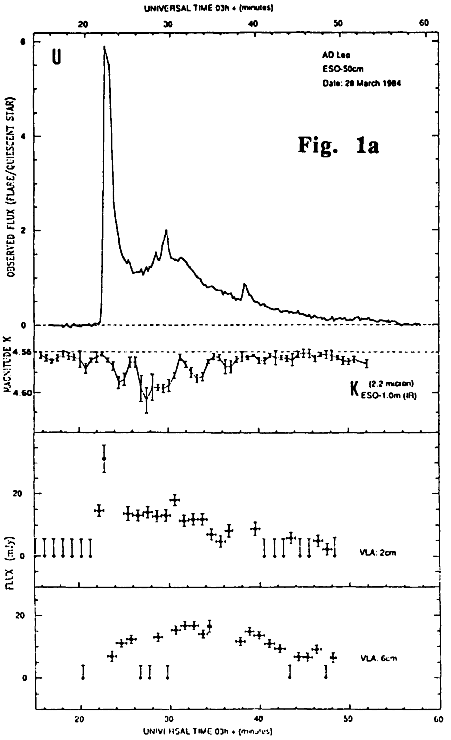

Fig. 1a

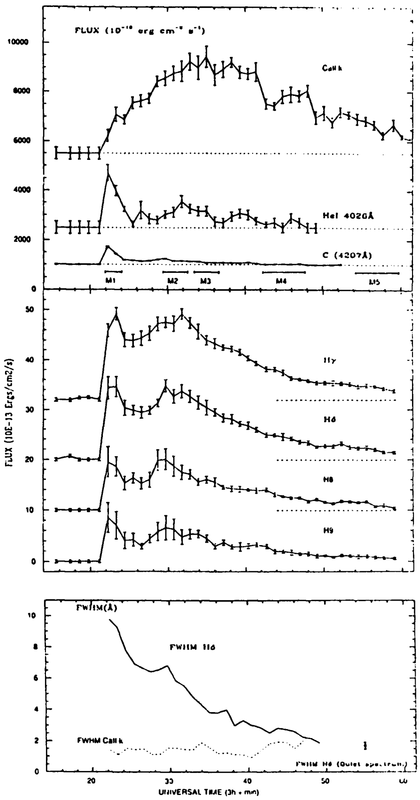

Fig. 1b

Fig.1 - Multiwavelength observations of a flare from AD Leo on 28 March 1984. From top to bottom: **(a)** optical continuum emission, IR emission in the K band, radio emission at 2 cm and 6 cm **(b)** Ca II K line emission, He I 4026 line emission, Balmer line emission and line widths as a function of time. The time scale is in minutes (from Rodonò et al. 1989)

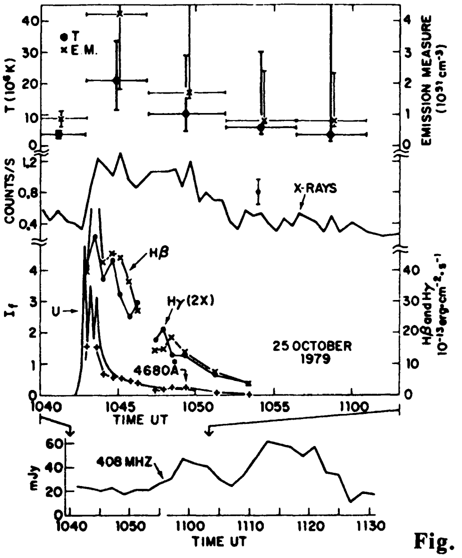

Fig. 2

Fig. 2 - Multiwavelength observations of a flare from YZ CMi on 25 October 1979. From top to bottom: coronal temperature and emission measure, soft X-ray emission, Balmer line and continuum emission, radio emission at 408 MHz (from Kahler et al. 1982).

different conditions occurring in a flaring atmosphere. It is not known whether similar phenomena occur in solar flares. Curiously enough, there are virtually no observations of solar flares at IR wavelengths. A search for solar counterparts of these "negative" IR flares could provide important insights into the physical conditions of both solar and stellar flares.

2.2 Optical/UV line emission

Optical line emission (Balmer series, Ca II H and K lines, He I, etc.) appear to be enhanced during stellar flares (Giampapa 1983, Worden 1983, Foing 1989). Typically, line emission peaks later than optical continuum emission, has a more gradual profile and a much longer duration (cf. Figs. 1 and 2). While an impulsive component is often present in the Balmer lines (in addition to the late gradual phase, cf. Fig. 1b), the Ca II lines show a more smooth behaviour and are further delayed with respect to the Balmer and continuum emission. The energy released in the Balmer lines is only a small fraction of the total energy released by the optical flare. Typically $E_{Balmer} \approx 3\ H\alpha \approx 0.1\ E_{opt}$. The electron densities estimated from the Balmer lines are in the range $\approx 10^{13}$ - 10^{14} cm^{-3}, not much larger than the typical densities derived for solar flares.

As shown by Fig. 1b, the Balmer lines are strongly broadened during the early-flare phases and the broadening decreases with time during the flare evolution. The Ca II lines are not broadened and this suggests that the broadening may be largely due to the Stark effect to which the Ca II lines are much less sensitive than the Balmer lines (Byrne 1989, Robinson 1989). Red asymmetries have also been observed during the early flare phases (Byrne 1989, Foing 1989). As will be discussed later, Stark-broadened profiles and red-asymmetries are important constraints on flare models.

UV lines (Lyα, Mg II , C II, C IV, N V, Si II, Si IV, He II) are also enhanced during flares indicating an increase of pressure in the stellar chromosphere and transition region at the time of flares. Unfortunately, UV observations of stellar flares with IUE have been severely hampered by the lack of sufficient sensitivity for time-resolved observations. In most cases, the typical exposure times needed to observe the star in the UV were comparable to the flare lifetime, with the consequence that only a coarse comparison could be made between flaring and quiescent conditions. In addition to UV lines, a strong UV continuum over the spectral band 1150 - 1950 Å is also observed during stellar flares (Bromage et al. 1986, Phillips 1989), similarly to what observed in stellar flares, but several orders of magnitude stronger.

Orders of magnitude estimates (Pettersen 1988, Byrne 1989) indicate that roughly equal amounts of energy are released in optical emission, in transition region UV emission and in soft X-rays. However, it is important to keep in mind that these estimates are largely based on observations of individual events and that simultaneous observations were available in only a few cases and only for a very limited number of spectral bands. Large variations are expected to occur from flare to flare. Considerable caution, therefore, should be exerted in using flux ratios at different frequencies for constraining flare models, at least until a much larger number of simultaneous multi-wavelength observations will become available.

2.3 X-ray emission

Flares from UV Ceti-type stars have been observed at soft ($\leq$ 10 KeV) X-ray energies by both the *Einstein* and EXOSAT Observatories. On the contrary, no hard X-ray observations of stellar flares have yet been possible, and there is no great hope that the situation will change in the near future. In solar flares the ratio of hard to soft X-rays is typically $\approx 10^{-5}$. If the same ratio applies to stellar flares, one would need detector areas as large as a soccer field. The hope is that the flux of hard X-rays from stellar flares may be larger (and the spectrum harder) than in solar flares. Even so, detection of hard X-rays from stellar flares would require major technological advances which at present are beyond the most optimistic expectations.

Fig. 2 shows an example of a soft X-ray flare observed with the *Einstein* Observatory. The flare coronal temperature reached a peak value of $\approx 20 \times 10^6$ K and the emission measure was a few times 10^{51} cm^{-3}. The *Einstein* observations of stellar flares were reviewed by Haisch (1983). With the launch of the EXOSAT Observatory our knowledge of stellar X-ray flares has increased enormously. The EXOSAT observations have been discussed most extensively by Pallavicini et al. (1989). There is a large variety of total energies and time scales for stellar X-ray flares. The time scales range from 10^2 to 10^4 sec and are similar to the typical time scales for solar X-ray flares. Also the coronal temperatures are similar to solar values and typically in the range 20 - 40 x 10^6 K. On the contrary, the emission measures and the total energies are much larger than for solar flares. The total X-ray energies range from 10^{30} to 10^{34} erg and the emission measures are in the range from 10^{51} to 10^{53} cm^{-3}. There is no direct measurement of flare coronal densities (as could be derived from ratios of density sensitive lines). Indirect estimates, based on radiative cooling times, suggest electron densities in the range 10^{11} - 10^{13} cm^{-3}.

The EXOSAT observations have suggested the existence of two different classes of stellar flares which might be the analog of solar compact and 2-ribbon flares (Pallavicini et al. 1989). Although this classification is based only on morphological evidence (the time scales and total energies being different in the two cases), it is tempting to speculate that these two classes may also correspond to different physical mechanisms, as believed to occur for solar flares (Pallavicini et al. 1977, Poletto 1989). We will come back later to the modelling of these two classes of stellar flares.

In analogy to what observed at optical wavelengths, there is a tendency of the largest X-ray flares to occur only on the most active stars. Observational selection effects may prevent small flares to be detected in intrinsically brighter stars. However, it is also true that in the EXOSAT sample no large flare was observed from intrinsically fainter stars, although one of them (UV Ceti) was observed for longer time than any other flare star. Note that the most active flare stars (in terms of their quiescent X-ray emission) are also the optically brightest since the quiescent X-ray luminosity appears to be proportional to the bolometric luminosity (Agrawal et al. 1986, Pallavicini et al. 1989). The average flare frequency distribution for all flare stars detected by EXOSAT is similar to the frequency distribution for optical flares, i. e. it follows a power-law $N(>E) \propto E^{-\alpha}$ with $\alpha = 0.7 \pm 0.1$ (in the optical case, α varies from 0.4 to 1.2 depending on the star while in the solar case $\alpha \approx 0.8$).

2.4 Radio emission

Radio flares from UV Ceti-type stars have been observed from centimetric to metric wavelengths (Gibson 1983, Dulk 1985, Kundu et al. 1987, 1988, Kuipers 1989, Lang 1989). Although energetically unimportant (the ratio of microwave to X-ray flux being typically on the order of 10^{-7} - 10^{-8}), microwave observations of stellar flares possess great diagnostic capabilities for the primary energy release process. Unfortunately, the interpretation of radio data is not straightforward and is usually heavily model dependent. Fig. 1a shows an example of a solar flare observed at 2 cm and 6 cm with the VLA. In this particular case, a good correspondence appears to be present between the optical continuum emission and microwave emission, especially at 2 cm. At first sight this correspondence might remind us of the good correlation known to exist for solar flares between microwave and hard X-ray bursts (if we take the stellar optical continuum emission as a proxy for hard X-ray emission, see above). However, it is important to stress that the correspondence shown by Fig. 1a is not typical of what observed in stellar flares. In most other cases there is a very poor correlation between radio and optical (as well as X-ray) flares (Nelson et al. 1986, Kundu et al. 1988).

Observations from the VLA have in fact provided ample evidence that fundamental differences exist between solar and stellar radio flares. Microwave flares from UV Ceti-type stars are often narrow-band ($\Delta\nu/\nu \leq 0.1$), have high brightness temperatures ($T_b \approx 10^{12}$ - 10^{15} K) and a high degree of circular polarization (up to 100%). These characteristics can only be explained by a coherent emission mechanism which remains largely unknown (electron cyclotron maser or some form of plasma radiation are the most frequently cited candidates, cf. Kuipers 1989). On the contrary, microwave flares from the Sun are most often produced by an incoherent emission mechanism which has been identified as non-thermal gyrosynchrotron emission. The poor correlation found in most cases between stellar microwave flares and optical/X-ray flares is consistent with the coherent nature of most stellar radio flares (since optical and X-ray emission are certainly incoherent).

We also recall that stellar flares at metric wavelengths are often delayed with repect to optical flares (an example at decimetric wavelengths is shown in Fig. 2). This is similar of what observed in solar flares and suggests the presence of disturbances moving throught the coronae of UV Ceti-type stars.

3. Models

There is no comprehensive theory capable of explaining the ensemble of the observational data mentioned above. The attempts made so far have been aimed at explaining some particular aspects of the flare problem, e.g. the optical continuum emission or the evolution of the high-temperature coronal region or the mechanisms responsible for the observed radio emission. The large majority of these attempts (with the only possible exception of stellar radio models) have been developed in the framework of the solar analogy by assuming that the same basic physical processes are operating in both cases, although on a vastly different energy scale and under different physical conditions. It may be questioned whether this approach is reasonable in view of the many differences that indubitably exist between solar and stellar flares (e.g. the energies involved are orders of magnitude larger, the relevant length scales and magnetic field strengths are also probably larger, and the radio emission mechanisms are certainly different).

There are several reasons why the solar analogy should be pursued further in studying stellar flares. First, all attempts that were made in the past to explain UV Ceti-type flares with non-solar models (see, e.g., review by Gurzadyan 1980) have encountered severe difficulties and had to be abandoned as soon as more stringent observational constraints became available. Secondly, in spite of the differences, the number of analogies that appear to be present between solar and stellar flares is so high (see section 2 above) that an investigation of solar-type models under stellar conditions is certainly warranted. This is not to say that solar-type models will be able to explain all phenomena observed in stellar flares, but at least it should be possible to determine what can be explained (if anything) by solar-type models and what cannot. Even in the case that solar models should prove totally inadequate, the investigation of them under stellar conditions is important since it will allow us to gain a much better understanding of the basic mechanisms of solar activity.

3.1 Solar flare loop models

Before considering the application of solar-type models to stellar conditions it may be useful to briefly recall the main features of current solar flare models. We will start with loop models, i.e. models which assume that the flare energy is released within one or more loop-like structures which remain magnetically confined throughout the flare (we will consider later the case when the magnetic configuration is assumed to be disrupted at the flare onset; cf. section 3.7 below).

Two very popular flare loop models are the so-called *thick-target* and *thermal* models (see, e.g., Dennis and Schwartz 1989, Emslie 1989). Both assume that energy is injected impulsively in the coronal portion of a magnetic arch whose footpoints are anchored in dense chromospheric and photospheric layers. In the thick-target model the primary energy release produces a large number of accelerated particles (either electrons or protons). In the most commonly accepted version of this model, the particles are mainly low-energy electrons with cut-off energy $E_c \approx 20$ KeV. These electrons are channeled by the magnetic field towards the dense loop footpoints and produce hard X-rays by non-thermal bremsstrahlung (while the tail of the electron distribution produces microwave emission by the gyrosynchrotron process). Most of the electron energy, however, is deposited at the loop footpoints by collisional losses, thus producing the observed optical and UV line and continuum emission, as well as the white-light flare. Collisional heating at the loop footpoints, in turn, produces evaporation of high-temperature plasma which fills the structure and is ultimately responsible for the observed (thermal) soft X-ray emission.

In the thermal model, the energy released produces mainly heating in the coronal portion of a loop. Energy is transferred downward by a conduction front and the lower atmospheric layers (that are responsible for the observed UV and optical emission) are heated by thermal conduction rather than by non-thermal particles. In this model hard X-rays are produced thermally in the high-temperature region created by the initial energy deposition. Also in this case, however, the large heat flux deposited at the loop footpoints produces evaporation of chromospheric material and hence the filling of the structure with high-temperature soft X-ray emitting plasma.

Although we have sketched these two models as completely separate one from the other, there is ample evidence from solar observations that both thermal and non-thermal processes occur in the same events. What is not known is the relative importance of thermal vs. non-thermal processes in the overal flare energy budget. Similarly, if stellar flares are analogous to solar flares, we may expect that the same basic ingredients (i.e. electrons or proton beams, thermal conduction, evaporation of dense chromospheric material etc.) should also be present in the stellar case. The relevant question is thus how these various energy transport mechanisms are operating in the different physical conditions of M dwarfs. We recall that the masses, radii and effective temperatures of these stars are substantially smaller than the corresponding values for the Sun ($M_* \approx 0.1 - 0.5\ M_o$, $R_* \approx 0.2 - 0.6\ R_o$, $T_{eff} \approx 2800 - 3500$ K), the photospheric densities are at least a factor 10 higher and the surface gravities are a factor 2 to 4 higher.

3.2 Heating by low-energy electrons: gasdynamic effects

Katsova and Livshifts were probably the first to call attention to the importance of gasdynamic effects in explaining the observed properties of stellar flares. In a series of papers that span almost a decade (e.g. Katsova et al. 1981, Livshits et al. 1981, Katsova and Livshits 1988, Katsova et al. 1989) they have investigated a model that is basically an estension to stellar conditions of the gasdynamic model originally developed for solar conditions by Kostyuk and Pikel'ner (1974). They assume that energy is deposited in the upper chromosphere by a flux of non-thermal electrons with a power-law energy distribution $N(E) \propto E^{-3}$ with cut-off energy $E_c \approx 20$ KeV. The spectrum and cut-off energy of these electrons are similar to those derived for solar flares from observations of hard X-ray bursts (Dennis and Schwartz 1989).

The high pressure region produced by the heating generates two perturbations, one upward (which drives chromospheric evaporation and leads to the formation of the soft X-ray emitting region) and one downward towards deeper chromospheric layers. The flare evolution is determined by the gasdynamic response of the atmosphere to the heating perturbation and can be described by solving the full set of time-dependent mass, energy and momentum equations for a prescribed geometry and assigned boundary conditions. Since the authors were mainly concerned with the optical properties of the flare, they treated in detail only the perturbation propagating downward through the optically-thick chromospheric layers (for a more detailed treatment of the gasdynamics in the optically-thin upper portion of the flaring structure see section 3.5 below).

From the upper chromosphere, where the non-thermal electrons are collisionally stopped, energy is transported downward by a conduction front and by a shock wave which precedes the thermal wave. A narrow ($\Delta L \approx 10$ Km) high-density ($n_H \approx 10^{15}$ cm^{-3}) region at $T \approx 10^4$ K forms behind the shock front and the emission from this region is capable of explaining the observed properties of the optical flare. An interesting prediction of the model is that the Balmer lines should be Stark-broadened (because of the high density of the emitting region) and should also be red-shifted, in qualitative agreement with stellar flare observations. This two-step process, however, is not very efficient and a large energy flux ($F_o \approx 10^{12}$ erg cm^{-2} s^{-1}) must be deposited in the upper chromosphere to produce a perturbation sufficiently strong to give the optical continuum flare. Moreover, the assumed geometry is somewhat idealized (a plane-parallel open atmosphere) and the flare evolution has been followed only for the first few tens of seconds (the heating is assumed to operate for 10 sec). In spite of these drawbacks, the model is intesting in so far it tries to explain the flare by consistently solving the full set of hydrodynamic equations including (at least partially) radiative transfer effects.

3.3. Heating by thermal conduction

An essential condition for the Livshits and Katsova model to work is that low-energy electrons (with E_c as low as ≈ 20 KeV) can penetrate in a stellar atmosphere as deep as the upper chromosphere. Mullan (1989) has argued that this is not possible in stellar conditions since flaring loops in M dwarfs are expected to be longer and denser than for solar flares. The penetration depth of an electron of energy E_{KeV} is given by

$$\xi_p(E) \approx 7 \times 10^{19}\ (E_{KeV}/20)\ \mathrm{cm}^{-2} \qquad (2)$$

while the expected column density of a flaring loop is $\xi(\mathrm{loop}) = \langle n \rangle L \approx 10^{21} - 10^{23}$ cm^{-2} $\gg \xi_p(20$ KeV). Hence, low energy electrons will be effectively stopped in the corona and energy will be transported downward by thermal conduction (Mullan 1976, 1977, Kodaira 1977). Note that in this model the observed ratio of X-ray to optical flare luminosity L_x/L_{opt} is a measure of the relative importance of conduction and radiative losses since $L_X/L_{opt} \approx \tau_c/\tau_r$. On average, this ratio is on the order of 1 in stellar flares (cf. Byrne 1989) but substantial variations can occur from flare to flare and even in the course of the same event.

It seems unlikely that a purely conductive model can explain the impulsive continuum emission. Temporal variations as short as 0.1 sec are observed in the light curve of optical flares (cf. Gershberg 1989), while the shortest time variations expected from a conductive model should be of the order of L/c_s, where L is the loop semilength and c_s is the sound speed. Since c_s is of the order of 500 - 1000 Km s^{-1} in typical flare conditions, one expects variations on time scales longer than several tens to a few hundred seconds if the optical flare is heated by thermal conduction.

There are other ways by which one could discriminate between thermal and non-thermal models. As shown by Cram and Woods (1982) and Canfield et al. (1984), heating of the chromosphere by non-thermal electrons produces Stark-broadened Balmer lines with central reversals. On the contrary, heating by conduction would produce narrow Balmer lines with weak or no central reversal. Solar observations (cf. Canfield et al. 1984) favor a non-thermal model during the impulsive phase of flares and the observed broadening of Balmer lines in the initial phase of stellar flares also argue against a purely thermal model. However, thermal conduction may become an important energy transfer mechanism during the later gradual phase of solar and stellar flares.

3.4 Penetration of high-energy particles to deep layers

The argument presented by Mullan (1989) against heating by non-thermal electrons does not hold if the accelerated particles in stellar flares have energies much larger than those typically encountered in solar flare conditions. From an analysis of optical continuum emission of stellar flares, Grinin and Sobolev (1977) concluded the the typical hydrogen densities in optical stellar flares should be as high as $n_H \approx 10^{15}$ - 10^{17} cm^{-3} and the optical thickness in the continuum $\gg 1$, in contrast to the solar case where τ_{cont} is always ≤ 1. From this they argue that continuum emission in stellar flares may originate from direct heating of deep chromospheric and photospheric layers by non-thermal particles with energy larger than in solar flares (Grinin and Sobolev 1989). Two possibilities have been considered: either electrons with energy higher than $\approx$ 100 KeV or protons with energy higher than $\approx$ 5 MeV (protons have also been proposed on different grounds by van den Oord 1988 and Simnett 1989).

Calculations carried out by Grinin and Sobolev (1989) show that protons with a power-law energy spectrum $N_p(E) \propto E^{-3}$ at energies $E \geq 5$ MeV could reproduce the optical continuum emission of stellar flares provided the energy flux carried by protons is $F_p \approx 10^{11}$ erg cm^{-2} s^{-1}. This is about one order of magnitude less that what required by the two-step model of Katsova and Livshifts (see section 3.2 above). Notice that in this model the heating of deep atmospheric layers is produced by both the protons and the optical and UV photons created as the beam penetrates the dense atmospheric layers. The heating due to photons actually penetrates deeper and has a larger amplitude than direct particle heating.

It is not possible at present to discriminate between proton heating and a model in which the same energy input is provided by electrons with energy $E_e = E_p\ (m_e/m_p)^{1/2} \approx E_p/50$. Hard X-ray and γ-ray observations of stellar flares could in principle discriminate between these two possibilities, in addition to providing information on the energy spectrum of accelerated particles. Unfortunately, the feasibility of such observations is far beyond the present capabilities.

3.5 Formation of the high-temperature region

The models discussed above were all concerned with the optical flare and hence with the lower atmospheric levels. The advent of X-ray observations from space has raised interest in models wich deal with the upper atmospheric levels and with the formation of the high-temperature soft X-ray emitting region. The physics of this region cannot be decoupled from the processes which occur at the lower levels. In practice, however, the difficulty of treating the full set of gasdynamic equations in the presence of radiative transfer effects has lead to a virtual decoupling of the lower and upper sections of the same flaring structure. Thus, while Katsova and Livshits (1988) were mainly concerned with the physical processes in the optically-thick chromospheric levels, another class of models have been developed to treat the upper sections of a flaring loop structure. These models assume that the plasma is optically-thin (as is true in the transition region and corona) and treat the chromophere only as a boundary layer and a mass reservoir.

Extensive work has been done in the solar case to model the hydrodynamics of the coronal portion of flaring loops both for the case of thermal heating and for heating by non-thermal particles (Nagai 1980, Pallavicini et al. 1983, Cheng et al. 1983, Nagai and Emslie 1984, MacNeice et al. 1984, Fisher et al. 1985, Peres et al. 1987, Peres 1989). An essential feature of these models is the prediction that a soft X-ray emitting region should form as a consequence of chromospheric evaporation when the chromosphere receives more energy than can be radiated away. The predictions of the models have been shown to be in reasonable agreement with the overal evolution of the high temperature flare plasma, in spite of the simplified treatment of many important physical processes (see discussion in Emslie 1989). It is interesting to see whether the same type of models can also reproduce soft X-ray observations of stellar flares. Unfortunately, very little work has yet been made in this area.

Reale et al. (1988) have applied their solar-type hydrodynamic code to a moderate size flare observed from Prox Cen. Formal agreement between model predictions and the time evolution of the soft X-ray flux is obtained for a loop structure with semilength $L=7 \times 10^9$ cm heated for ≈ 700 sec (i. e. only during the rise phase of the flare) with a constant heating flux of $F_H = 1.25 \times 10^{10}$ erg cm^{-2} s^{-1}. From this they conclude that the loop structure involved in the flare was much larger with respect to the stellar radius than in the solar case. Although attractive, this model is not free from difficulties. First, the large size of the flaring loop implies that the structure was almost empty in the preflare state, since the derived semilength is about 4 times larger than the hydrostatic scale height at typical preflare temperatures. Moreover, only the early decay phase of the flare was reproduced and additional heating in the late-decay would be required to reproduce the observed long decay of the flare. Finally, and more importantly, the model may not be unique. For instance, a longer lasting heating in a shorter loop will probably reproduce the data at least as well.

The above difficulties show that more numerical simulations need to be carried out for a variety of different stellar conditions. Work is in progress (e.g. Cheng and Pallavicini 1989) to build a grid of stellar hydrodynamic models in order to explore the effects of different physical parameters on the dynamic evolution of stellar flares. Unfortunately, this type of numerical calculations are very demanding in terms of computer resources and progress in this area is occurring at a very slow rate. Furthermore, the larger energy input that is necessary to deposit in the stellar case affects severely the lower sections of the structure down to photospheric levels. It is questionable whether in this case neglecting radiative transfer effects and a proper treatment of the lower atmosphere is an acceptable approach.

Recently, Fisher and Hawley (1988) have developed a simplified algorithm to evaluate in an approximate way the time evolution of coronal temperature, pressure and emission measure without recourse to time consuming numerical calculations. They have applied the method to a large flare on AD Leo predicting the time evolution of coronal temperature and emission measure. While the derived peak values ($T \approx 25 \times 10^6$ K, EM ≈ 10^{52} cm^{-3}) are in reasonable agreement with typical values for stellar flares (see section 2.3 above), there were no soft X-ray observations available for this specific event. Therefore, the ability of the model to reproduce actual stellar flare observations remains to be determined.

3.6 Heating by soft X-ray irradiation.

In principle, one could test the predictions of Fisher and Hawley (1988) for the flare on AD Leo by using optical data (that were available for that particular event). In order to do that, one needs to relate the observed optical emission to the parameters of the high-temperature region by assuming a specific mechanism for transferring energy from the upper to the lower levels. This has been done by Hawley (1989) who has assumed that chromospheric heating during the flare results from "backwarming" by soft X-ray and UV radiation (see also early suggestions by Somov 1975 and Cram 1982).

In brief, the reasoning of Hawley (1989) goes as follows. Balmer line emission depends on the temperature structure in the chromosphere. If the chromosphere is heated by soft X-ray irradiation, the chromospheric temperature structure and the Balmer line emission can be parameterized as a function of the coronal temperature at the apex of the flaring loop. From the observed time evolution of the Balmer lines one can predict therefore the time evolution of the coronal apex temperature. For self-consistency, the predicted temperature evolution should be equal to that predicted by gas-dynamic coronal models such as those discussed in the previous section. Preliminary results published by Hawley (1989) show only a limited agreement between the two predicted temperature evolutions. However, the model is interesting both because it attempts to solve the whole flare problem in a self-consistent way and because it calls attention to soft X-ray irradiation as a mechanism for heating the optical region. It is interesting to observe that a good correlation has recently been found between Hγ and soft X-ray emission in stellar flares (Butler et al. 1989). Whether this correlation is due to soft X-ray irradiation of the lower atmospheric levels remains, however, unclear. Note that the mechanism suggested by Hawley predicts that the flare seen in the Balmer lines should cover an area much larger than that of the optical continuum flare, if the latter is produced -as usually assumed- by non-thermal particles. This is reminiscent of what typically observed in solar flares.

3.7 Two-ribbon flares

In the models above we have assumed that the flare occurs in a magnetically confined loop-like structure that remains virtually unchanged troughout the flare evolution. On the Sun, this is believed to occur only for compact short-lived events. There is, however, another class of solar flares, the so-called long-duration 2-ribbon flares, in which the magnetic configuration is disrupted at the flare onset and energy is gradually released as the magnetic field lines relax back to a closed configuration. This type of events were first modelled by Kopp and Pneuman (1976; see also Cargill and Priest 1983). Kopp and Poletto (1984) have shown that the model is indeed capable of reproducing the main features of solar 2-ribbon flares.

Soft X-ray observations of stellar flares with the EXOSAT Observatory have shown the existence of intense long-duration stellar flares which are strongly reminiscent of solar two-ribbon flares (Pallavicini et al. 1989). The long-decay of these flares indicates that energy must be continuosly provided troughout a large part of the flare decay. The interesting question is whether a reconnection model such as that proposed by Kopp and Pneuman could also explain this type of stellar events.

Poletto et al. (1988) and Poletto (1989) have addressed this question by applying the reconnection model to a few long-duration stellar flares as well as to solar-flares observed by full-disk X-ray instruments. In the latter case, the flares are observed as if they were stellar flares, but the parameters predicted by the model can be directly compared with those observed with high-resolution instruments. In all cases, the reconnection model appears to be capable of reproducing the time evolution and intensity of the flare radiative power, but is unable to uniquely determine the best fit parameters of the model and, hence, the interesting physical properties of the flaring region.

The intrinsic limitations of the reconnection model when applied to stellar conditions are readily apparent. There are three free parameters in the model: the size of the flare region, the strength of the magnetic field at photospheric level and the speed at which the system relaxes from an open to the closed configuration. In the solar case the latter quantity is measured by the velocity V_0 at which the reconnection point moves upwards as new closed loops form (see details in Poletto 1989). The time profile of the energy released by reconnection is determined almost uniquely by V_0. The other two parameters play only the role of a scaling factor, larger energy releases being obtained by either larger regions or higher magnetic field strengths. Therefore, in the absence of spatial information or other diagnostics (such as, for instance, density measurements), it is impossible to determine uniquely the spatial scale and magnetic field strength in stellar flares. Moreover, the agreement that can be obtained between model predictions and observations cannot be taken as a proof that long-duration stellar flares are indeed produced by a reconnection process as that envisaged by Kopp and Pneuman (1976). As the matter of fact, the same stellar flare (on Prox Cen) has been modelled as a compact flare by Reale et al. (1988) and as a 2-ribbon flare by Poletto et al. (1988).

4. Concluding remarks

From what we have discussed above, it should appear clear that the fundamental question whether stellar flares can be explained by scaled-up versions of solar-type models cannot be answered as yet. This is not only because the extensions of solar models to stellar conditions is still in a rudimentary stage. More importantly, in the stellar case there appears to be a lack a sufficient observational constraints to tests models and to discriminate between various alternatives.

In the solar case, there is a wealth of observational data and a number of sophysticated models to interprete these data. Although we are still far from a complete flare theory, there is some realistic hope that substantial progress can be reached on a relatively short time scale by an appropriate combination of additional observations and improved theoretical models. This is not the case for stellar flares. In this case, the paucity of the observational data is such that finding formal agreement between model predictions and observations may even result relatively simple. However, one has to worry about unicity and physical consistency of the proposed models. We have given several examples of this situation in the sections above.

In our opinion, substantial progress in the study of stellar flares can only be reached by major advances on the observational side, and particularly by the access to new diagnostic capabilities (e.g. hard X-rays, γ-rays) as well as by vastly improved sensitivity and spectral resolution at optical, UV and soft X-ray wavelengths. Unfortunately, this is not a programme that can expected will be completed in the next few years.

References

Agrawal, P.C., Rao, A.R. and Sreekantan, B.V.: 1986, *Montly Not. Roy. Astron. Soc.* **219**, 225.

Byrne, P.B.: 1989, *Solar Phys.* **121**, 61.

Byrne, P.B.: 1983, in *Activity in Red-dwarf Stars* (P.B. Byrne and M. Rodonò eds.), p. 157.

Byrne, P.B. and Rodonò, M. (eds.): 1983, *Activity in Red-dwarf Stars*, Reidel Publ. Co., Dordrecht.

Bromage, G.E., Phillips, K.J.H., Dufton, P.L. and Kingston, A.E.: 1986, *Montly Not. Roy Astron. Soc.* **220**, 1021.

Butler, C.J., Rodonò, M. and Foing, B.H.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 21.

Canfield, R.C., Gunkler, T.A. and Ricchiazzi, P.J.: 1984, *Astrophys. J.* **282**, 296

Cargill, P.J. and Priest, E.R.: 1983, *Astrophys. J.* **266**, 383.

Cheng, C.C., Oran, E.S., Doschek, G.A., Boris, J.P. and Mariska, J.T.: 1983, *Astrophys. J.* **265**, 1090.

Cheng, C.C. and Pallavicini, R.: 1989, in preparation.

Cram, L.E.: 1982, *Astrophys. J.* **253**, 768.

Cram, L. and Woods, T.: 1982, *Astrophys. J.* **257**, 269.

Dennis, B.R. and Schwartz, R.A.: 1989, *Solar Phys.* **121**, 75.

Dulk, G.A.: 1985, *Ann. Rev. Astron. Astrophys.* **23**, 169.

Emslie, G.A.: 1989, *Solar Phys.* **121**, 105.

Fisher, G.H., Canfield, R.C. and McClymont, A.N.: 1985, *Astrophys. J.* **289**, 414.

Fisher, G.H. and Hawley, S.L.: 1988, submitted to *Astrophys. J.*

Foing, B.H.: 1989, *Solar Phys.* **121**, 117.

Gershberg, R.E.: 1989, *Memorie Soc. Astron. It.* **60**, 263.

Gershberg, R.E. and Shakhovskaya, N.I.: 1983, *Astrophys. Space Sci.* **95**, 235.

Giampapa, M.S.: 1983, in *Activity in Red-dwarf Stars* (P.B. Byrne and M. Rodonò eds.), p. 223.

Gibson, D.M.: 1983, in *Activity in Red-dwarf Stars* (P.B. Byrne and M. Rodonò eds.), p. 273.

Gondhalekar P.M. (ed.): 1986, *Flares: Solar and Stellar*, Rutherford-Appleton Laboratories, Abingdon.

Grinin, V.P. and Sobolev, V.V.: 1977, *Astrofizika* **13**, 587.

Grinin, V.P. and Sobolev, V.V.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 297.

Gurzadyan, G.A.: 1980, *Flare Stars*, Pergamon Press, Oxford.

Haisch, B.M.: 1983, in *Activity in Red-dwarf Stars* (P.B. Byrne and M. Rodonò eds.), p. 255.

Haisch, B.M. and Rodonò, M. (eds.): 1989, *Solar and Stellar Flares - Poster Papers*, Catania Astrophys. Obs. Special Publication [see also *Solar Physics* **121** (1989)].

Havnes, O., Pettersen, B.R., Schmitt, J.H.M.M. and Solheim, J.E. (eds.): 1988, *Activity in Cool Star Envelopes*, Kluwer Acad. Publ.: Dordrecht.

Hawley, S.L.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 49.

Kahler, S. and other 30 authors: 1982, *Astrophys. J.* **252**, 239.

Katsova, M.M., Kosovichev, A.G. and Livshits, M.A., 1981, *Astrofizika* **17**, 285.

Katsova, M.M. and Livshits, M.A.: 1988, in *Activity in Cool Star Envelopes* (O. Havnes et al. eds.), p. 143.

Katsova, M.M., Livshits, M. A, Butler, C.J. and Doyle, J.G.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 87.
Kodaira, K.: 1977, *Astron. Astrophys.* **61**, 625.
Kopp, R.A. and Pneuman, G.W.: 1976, *Solar Phys.* **50**, 85.
Kopp, R.A. and Poletto, G.: 1984, *Solar Phys.* **93**, 351.
Kostyuk, N.D. and Pikel'ner, S.B.: 1974, *Astron. J. of USSR* **51**, 1002.
Kuipers, J.: 1989, *Solar Phys.* **121**, 163.
Kundu, M.R., Jackson, P.D., White, S.M. and Melozzi, M.: 1987, *Astrophys. J.* **312**, 822.
Kundu, M.R., Pallavicini, R., White, S.M. and Jackson, P.D.: 1988, *Astron. Astrophys.* **195**, 159.
Kundu, M.R., Woodgate, B. and Schmahl, E.J. (eds.): 1989, *Energetic Phenomena on the Sun*, Kluwer Acad. Publ., Dordrecht.
Lacy, C.H., Moffett, T.J. and Evans, D.S.: 1976, *Astrophys. J. Suppl.* **30**, 85.
Lang, K.R.: 1989, in *Flare Stars in Star Clusters, Associations and Solar Vicinity* (L.V. Mirzoyan ed.), in press.
Livshits, M.A., Badalyan, O.G., Kosovichev, A.G. and Katsova, M.M.: 1981, *Solar Phys.* **73**, 269.
MacNeice, P., McWhirter, R.W.P., Spicer, D.S. and Burgess, A.: 1984, *Solar Phys.* **90**, 357.
Mirzoyan, L.V. (ed.): 1989, *Flare Stars in Star Clusters, Associations and Solar Vicinity*, Kluwer Acad. Press, Dordrecht (in press).
Mullan, D.J.: 1976, *Astrophys. J.* **207**, 289.
Mullan, D.J.: 1977, *Solar Phys.* **54**, 183.
Mullan, D.J.: 1984, *Astrophys. J.* **279**, 746.
Mullan, D.J.: 1985, in *Radio Stars* (R. M. Hjellming and D.M. Gibson eds.), p. 173.
Mullan, D.J.: 1989, *Solar Phys.* **121**, 239.
Nagai, F.: 1980, *Solar Phys.* **68**, 351.
Nagai, F. and Emslie, A.G.: 1984, *Astrophys. J.* **279**, 896.
Neiding, D.F.: 1989, *Solar Phys.* **121**, 261.
Nelson, G.J., Robinson, R.D., Slee, O.B., Ashley, M.C.B., Hyland, A.R., Touhy, I.R., Nikoloff, I. and Vaughan, A.E.: 1986, *Montly Not. Roy Astron. Soc.* **220**, 91.
Pallavicini, R., Peres, G., Serio, S., Vaiana, G.S., Acton, L., Leibacher, J. and Rosner, R.: 1983, *Astrophys. J.* **270**, 270.
Pallavicini, R., Serio, S. and Vaiana, G.S.: 1977, *Astrophys. J.* **216**, 108.
Pallavicini, R. and Tagliaferri, G.:1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and Rodonò eds.), p. 17.
Pallavicini, R., Tagliaferri, G. and Stella, L.: 1989, *Astron. Astrophys.*, in press.
Peres, G.: 1989, *Solar Phys.* **121**, 289.
Peres, G., Reale, F., Serio, S. and Pallavicini, R.: 1987, *Astrophys. J.* **312**, 895.
Pettersen, B.R.: 1988, in *Activity in Cool Star Envelopes* (O. Havnes et al. eds.), p. 49.
Pettersen, B.R.: 1989, *Solar Phys.* **121**, 299.
Pettersen, B.R., Coleman, L. A. and Evans, D.S.: 1984, *Astrophys. J. Suppl.* **54**, 375.
Phillips, K.J.H.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 45.
Poletto, G.: 1989, *Solar Phys.* **121**, 313.
Poletto, G., Pallavicini, R. and Kopp, R.A.: 1988, *Astron. Astrophys.* **201**, 93.
Reale, F., Peres, G., Serio, S, Rosner, R. and Schmitt, J.H.M.M.: 1988, *Astrophys. J.* **328**, 256.
Robinson, R.D.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 83.
Rodonò, M. and other 9 authors: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 53.
Shakhovskaya, N.I.: 1989, *Solar Phys.* **121**, 375.
Simnett, G.M.: 1989, in *Solar and Stellar Flares - Poster Papers* (B.M. Haisch and M. Rodonò eds.), p. 357.
Somov, B.V.: 1975, *Solar Phys.* **42**, 235.
Sturrock, P.A. (ed).: 1980, *Solar Flares*, Colorado Assoc. Univ. Press, Boulder, Co.
Svestka, Z.: 1976, *Solar Flares*, Reidel Publ. Co., Dordrecht.
van den Oord, G.H.J.: 1988, *Astron. Astrophys.* **207**, 101.
Worden, S.P.: 1983, in *Activity in Red-dwarf Stars* (P.B.Byrne and M. Rodonò eds.), p. 207.

DISCUSSION

SIVARAM: (i) Have there been observations of flares from red giants?
(ii) What about the durations and periodicities of stellar flares? Are they consistent with a Poisson process?

PALLAVICINI: (i) Flares have been occasionally reported from a few late-type giants and supergiants, but have not been confirmed (Pettersen 1989, Solar Phys. 121,299). The only evolved stars that have been confirmed to flare regularly are RSCVn and Algol-type binaries, WUMa binaries and FK Com stars.
(ii) As far as we know, there are no regularities observed in the periodicities and durations of stellar flares. Both are consistent with Poisson statistics.

KUIJPERS: In my view the important issue is not if the solar flare can be scaled up to the stellar case. Rather, it is if the various kinds of explosions on stars are also of magnetic origin, but under different conditions. For example, in the case of an accretion disk around a neutron star magnetic flares may be important in a radiation-dominated plasma; or, in the case of active galactic nuclei, flares may occur in an electron-positron plasma. So I would like to stimulate my colleagues very much to think of interesting physics for magnetic flares under conditions different from the Sun or dMe stars.

PALLAVICINI: Your point is well-taken. Certainly, we should address the flare problem with an open mind, especially in view of the fact that there are at least some differences between the solar and stellar flare, especially with regard to radio emission. Nevertheless, the analogy between solar flares and flares on dM stars is so strong that there are good reasons to investigate further the application of solar-type models to stars. This may not be well justified for other astrophysical objects, such as those you mentioned.

LANG: Scaled-up version of solar flares are *not* consistent with the radio data for dwarf m stars. The radio emission is often not correlated with the X-ray or optical emission from flare stars, whereas they are correlated on the Sun. Rise times of about 10 milliseconds for radio flares indicate that the size is relatively small(~ 3000km), not a scaled-up larger size. Coherent radiation mechanisms are required, and, if cyclotion maser emission applies, the magnetic fields are not exceptionally strong (~ a few hundred gauss).

PALLAVICINI: I agree with you that radio observations indicate the existence of fundamental differences between solar and stellar flares and, therefore, that scaled-up versions of solar flares may not be sufficient to explain stellar flares. On the other hand, there are also many similarities at other wavelengths between solar and stellar flares which argue for the common mechanism. The large sizes and/or higher magnetic fields that I have inferred for stellar flares derive from the *assumption* (which I have not attemped to justify) that the energy of stellar flares derives from magnetic fields as for the Sun. On the other hand, size and magnetic fields derived from radio observations are themselves model-dependent and I do not think you can settle the issue of size and magnetic field strengths from these data alone. The problem is that we still do not know whether solar and stellar flares derive from a common mechanism.

GANGADHONA: (i) What is the typical time scale over which the flare energy is released?
(ii) What is the frequency range over which energy is released?

PALLAVICINI: (i) The typical time scales for energy release in UV ceti-type flare stars are similar to those of solar flares. It is often mentioned that the time-scales of stellar flares are shorter than for solar flares, but I think this is a selection effect since stellar flares have been observed mostly in continuum optical emission which is typically more impulsive. In the Balmore lines and in soft X-rays there is virtually no difference in time scales between solar and stellar flares.
(ii) Energy is released in stellar flares at all frequencies that have been observed so far, *i.e.* optical, UV, soft X-ray, radio. We do not yet have observations of stellar flares in hard X-rays and γ-rays.

ALURKAR: Was the negative flare an isolated event? Is it specific to a particular class of stars or is it an absorption line?

PALLAVICINI: Infrared stellar flares have been observed so far in only two cases, but this may be due to the fact that there were no previous observations in the infrared. We cannot say, therefore, if this is a general property of flare stars. The negative dip, observed in the k-band, is certainly not an absorption line, but we do not have yet any plausible mechanism to explain it, except that it is probably due to modifications of atmospheric structure and opacity effects. Observations are being planned to see whether negative IR flares occur on the Sun. So far we simply do not know if the same phenomenon occurs also on the Sun.

SHEVGAONKAR: (i) As we carry out more and more observations at longer radio wavelengths we find higher brightness temperatures ($\sim 10^{12} - 10^{14}$K). These can only be explained by a coherent mechanism or by a large source size ($\sim 100R_*$).
(ii) As you have mentioned, on flare stars the magnetic field and density are large, so the sight for coherent emission must be above the gyro-resonance levels. At that height the magnetic fields, if they are similar to that on the Sun, must have a simple configuration. Why then are there frequent coherent flares on the flare stars but not on the Sun?

PALLAVICINI: (i) Your point is well taken. (ii) I do not have any simple answer. We do not know the strength and topology of magnetic fields in flare stars. At this stage we can only make conjectures, but this will not help much in answering your question.

DAVILA: We know that on the Sun flares exhibit 155-day periodicity. Are there stellar observations with sufficient time coverage to determine whether a similar phenomenon occurs on other stars?

PALLAVICINI: Flare stars have been observed at optimal wave lengths for a long-time and periodicities have been sometimes reported. None of these periodicities, however, have been confirmed and the general belief at present is that stellar flares occur randomly in time. Thus no 155-day periodicity has been found so far for stellar flares, but certainly it would be useful to look again at the data or at future data in search of such a periodicity.

VAHIA: Pye and McHardy have explained flares on RSCVn binaries as magnetic loops of interbinary sizes. Does the fact that most of our flare stars are in binaries have any bearing on the flare characteristics of flare stars?

PALLAVICINI: I purposely excluded RSCVn binaries and PMS stars from my talk, because there are many indications that flares on these stars are fundamentally different from solar flares and from flares on UV Ceti-type stars. It is well possible that interconnecting loops are involved in flares in RSCVn binaries. However, I do not think that binarity has any effect on flares on UV Ceti-type stars, since these stars are not close binaries. The typical distances between components of UV Ceti-type binaries are orders of magnitude larger than the stellar radius, contrary to what occurs in RSCVn binaries.