X-ray Coronae of Stars: Some Theoretical Questions

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Abstract. I discuss theoretical implications of X-ray observations of coronal emission in stars, with an emphasis on coronal heating mechanisms and dynamo action, and on the modelling of quiescent and flaring coronal emission with solar-type loop models. I also report on the recent detection by BeppoSAX of hard (>20 keV) X-ray emission from stellar flares.

1. Introduction

The subject of stellar coronae and their X-ray emission has been reviewed many times recently (see, e.g., Pallavicini 1998 and references therein). In this volume, stellar coronal observations are reviewed by Stern (stellar magnetic activity and variability), Jeffries (X-ray stars in open clusters) and Walter (pre-main sequence stars), whereas some aspects of stellar coronal observations are also discussed by Linsky (magnetic activity across the HR diagram), Mathioudakis (coronal spectroscopy) and van den Oord (stellar flares). There is no point therefore in trying to summarize again our present observational knowledge of X-ray coronae. Rather what I will do here is to address a few selected theoretical questions in coronal physics that can be effectively tackled with X-ray observations. It is important to stress that our theoretical understanding and modelling of coronal emission in stars is still in a rather rudimentary stage in comparison to the wealth of data that have been gathered over the past twenty years. For late-type stars in particular, our theoretical understanding is largely based on the solar analogy and on the application to stars of models and concepts originally developed for the solar corona. Yet, in spite of the many limitations, we are starting to have a sufficiently accurate description of coronal emission at various stages in the evolution of low-mass stars, from the pre-main sequence contraction phase, to the hydrogen burning main-sequence phase, and to the post-main sequence expansion phase. By comparing spatially-unresolved stellar observations with the detailed knowledge we have of the solar corona, it is possible to investigate how coronal emission depends on parameters like mass, gravity, rotation, magnetic fields and age, i.e. on parameters for which only a single value is accessible in the case of the Sun. In addition, stellar phenomena often occur on a much larger energy scale than on the Sun, thus allowing us to study coronal processes under conditions of extreme activity.

There are many questions in stellar coronal physics that should be addressed. Let me list just a few of them:

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- **Coronal heating**: how the coronae of different types of stars (both hot and cool) are heated? Which is the role of winds (in hot stars) and of magnetic fields (in cool stars) in the heating process? How important are flares and micro-flares in producing the apparently quiescent X-ray emission of active stars?

- **Stellar dynamos**: how the coronal activity of low-mass stars depends on rotation and convection? Are there different types of dynamos for stars of different masses and/or different activity levels?

- **Stellar evolution**: how coronal activity varies in the course of stellar evolution? What is the origin of coronal emission in pre-main sequence stars? Why coronal emission disappears (or is drastically reduced) in red giants with large mass losses?

- **Coronal structures**: how stellar coronae are spatially and thermally structured? Are magnetically-confined loops, similar to those observed on the Sun, the coronal building blocks for all types of stars? How binarity affects the structure of coronae, particularly in close binary systems?

- **Coronal abundances**: are coronal and photospheric abundances different, as suggested by recent spectroscopic observations? Does a FIP effect exist for stellar coronal emission? Do elemental abundances vary during flares?

- **Coronal variability**: how stellar coronae vary on different time scales? What powers the very energetic flares (typically much stronger than solar ones) observed in stars? How realistic are the flare parameters inferred by applying solar-type models to stellar flares?

In the following, I will elaborate on some of the above problems, with emphasis on coronal heating and dynamo action, and on the modelling of stellar coronae and flares by means of loop-like structures.

2. **Coronal Heating and Dynamos**

It is generally accepted that coronal heating in late-type stars results from the dissipation of dynamo-generated magnetic fields, as is believed to occur for the Sun. Indirect evidence for this is provided by the observed dependence of coronal emission on rotation rate for F to M stars with outer convective zones (Pallavicini et al. 1981, Hempelmann et al. 1995). The exact functional dependence of this relationship is still a matter of debate, and it is not even clear whether the dependence is simply upon rotation rate or Rossby number, i.e. the ratio of rotation period to the convective turnover time. A dependence on Rossby number is more satisfactory from a theoretical point of view, since it involves both rotation and convection, i.e. the two factors that are most relevant for the efficiency of the dynamo process. However, for field stars there is little observational evidence that a formulation in terms of the Rossby number is better than in terms of rotation periods or \( v \sin i \). Much stronger evidence for a dependence on both rotation and convection is provided by observations of stars
in clusters. By observing stars in open clusters of different ages, in fact, one can compare homogeneous samples of stars with approximately the same age and chemical composition, but different masses. Thus, by observing stars with the same mass in different clusters, one can investigate the evolution of angular momentum and coronal emission as a function of age; conversely, by comparing stars of different masses in clusters, one can investigate how angular momentum evolution and coronal emission depends on convection zone properties. The extensive observations of open clusters carried out by ROSAT (Randich 1997 and references therein; see also Jeffries, this volume) have shown a general trend of decreasing coronal emission with age, as expected by loss of angular momentum on the main-sequence due to the braking action of stellar winds. They have also shown, however, that this overall decrease is itself a function of mass and of convection zone depth. G stars with shallow convective zones are braked much more efficiently than late-K and M dwarfs with deeper convection zones; therefore, coronal emission in G stars decreases more rapidly with age than for lower mass stars, consistently with what expected from simple dynamo models.

A further complication is the existence among active stars of a saturation limit (at $L_x/L_{bol} \sim 10^{-3}$), for which stars rotating more rapidly than a given threshold ($\sim 15 \ km \ s^{-1}$ for the Pleiades K stars) all have the same X-ray luminosity. The existence of saturation, together with a dependence of coronal emission on Rossby number, explains satisfactorily the observed pattern of coronal emission with age in clusters spanning the age range from $\sim 30$ Myr (like IC 2602 and IC2391) to $\sim 700$ Myr (the age of the Hyades).

The existence of a saturation limit is an important and still little understood problem ... see Mathioudakis (this volume). It could be due to a saturation of the dynamo process itself, or to the filling of the whole available coronal volume by active regions with a maximum temperature and pressure. If so, it remains to be determined why there is a maximum in the temperature and density of stellar active regions: it must result from the heating process itself, which however remains elusive. Recently, the phenomenon of “supersaturation” has also been discovered in cluster data, i.e. a turnover of coronal emission at still higher rotation velocities than those typical of the saturation regime (Randich 1998). This supersaturation effect is difficult to understand, unless it is only a selection effect due to higher plasma temperatures attained at very high rotation rates, which shift the observed coronal emission outside of the ROSAT passband. If on the contrary supersaturation is an intrinsic property of the dynamo process and/or of the heating mechanism, it provides an important clue, together with saturation, for understanding coronal heating and dynamo action in late-type stars. It should be emphasized that the physical link between coronal activity and the dynamo process is only indirect, and mediated through the efficiency of the coronal heating mechanism for stars of different spectral types and activity levels. The heating mechanism remains unknown (even for the Sun!), although it is generally accepted that it may result from the dissipation of either electric currents or of magneto-acoustic waves. Stellar coronal observations have provided compelling evidence that the heating mechanism must be magnetic in nature (a purely acoustic heating would have produced a strong dependence of coronal emission on spectral type and mass, which is not observed); yet, it has not been possible up to now to distinguish between alternative heating mechanisms.
If the efficiency of coronal heating is not a strong function of mass (which however remains to be proved), X-ray coronal observation can provide information on the dynamo process itself, and therefore on processes which occur in the deep interior of the star. The apparent decrease of coronal emission that has been reported from early *Einstein* observations of very-late M stars suggested that coronal activity could be reduced, or totally suppressed, in fully convective stars. If this is the case, a dynamo model operating in a shallow layer at the interface between the convective zone and the radiative interior (as thought to occur for the Sun) is favoured with respect to a distributed dynamo operating throughout the convective zone. More recent data from *ROSAT* (Fleming et al. 1993) do not support the view that coronal activity is suppressed in fully convective stars, and in fact there is no apparent decrease in coronal efficiency (as measured by the $L_x/L_{bol}$ ratio) for fully-convective stars. The vigorous coronal activity of pre-main sequence (PMS) stars also argues against such a possibility, thus favouring a distributed dynamo rather than a shallow dynamo at the bottom of the convective zone. It must be stressed however that our understanding of the dynamo mechanism is so imperfect that it would be dangerous to use these qualitative arguments, as well as the indirect evidence provided by coronal observations, to make strong statements about stellar dynamos. Similarly, while there is some indication (from both ground-based Ca II data and from coronal X-ray observations) that different types of dynamos (chaotic vs cyclic) may be at work in stars with widely different rotation rates and activity levels, the data are still insufficient to constrain dynamo models in an effective way.

An interesting and related question is the origin of coronal emission in PMS stars. It is now well established that PMS stars, both Classical T-Tauri (CTT) and Weak-lined T-Tauri (WTT) stars, are vigorous X-ray emitters. This extends the relationship between X-ray emission and rotation to ages at least as young as $\sim 1$ to $10$ Myr. Extensive observations by *Einstein* and *ROSAT* of PMS stars in star forming regions (SFR) in Taurus-Auriga, Chamaeleon, $\rho$ Oph, Lupus, Sco-Cen and other regions have revealed dozens of X-ray sources which were only partially coincident with previously known PMS stars (Neuhäuser 1997, Feigelson & Montmerle 1998, and references therein). X-ray surveys have proven to be the most effective way to identify young stellar objects and thus to determine in an unbiased way the Initial Mass Function of SFRs. The observed emission most likely originates from magnetic processes at the star surface (as in WTTs) and/or in magnetic structures which connect the central star to the surrounding disk (as may be the case, at least partly, for CTTs). The high level of time variability of these sources, with frequent long-duration flares, suggests that X-ray activity originates via magnetic reconnection as in solar flares. Determination of rotation rates of these stars by means of photometric and spectroscopic observations from the ground has shown, somewhat surprisingly, that PMS stars are in general not very fast rotators, with rotation rates ranging from a minimum detectable $v \sin i \sim 5 \ km \ s^{-1}$ up to $\sim 50 \ km \ s^{-1}$. On the contrary, stars in young clusters like $\alpha$ Per (with an age of 50 Myr) show a much broader range of rotational velocities, with values of up to $\sim 200 \ km \ s^{-1}$. This can easily be understood as a consequence of stellar spin-up as a PMS star approaches the ZAMS along the radiative track (Bouvier 1994). The broad range of rotational values shown by cluster stars is due to the different times scales for the dissipation of the disk during PMS evolution. Shorter time scales imply a larger
amount of spin-up and a higher velocity on the ZAMS; on the contrary, a longer
time scale for the dissipation of the disk implies a stronger coupling between
the star and the disk and a smaller amount of spin-up. The study of angular
momentum evolution is thus fundamental for understanding coronal activity in
PMS stars as well as in the subsequent evolution on the main-sequence (Bouvier
1997).

3. Modelling of Quiescent Coronae

For only a small number of stars (typically eclipsing binaries) it is possible, at
least in principle, to obtain direct information on the spatial structure of their
coronae. For all the others, we must rely on indirect evidence such as provided,
for instance, by a model-dependent analysis of their temperature structure. X-
ray spectra of stellar coronae are usually fitted by one (1-T) or two (2-T) tem-
perature isothermal models, which provide a crude description of the corona in
terms of a minimum numbers of parameters: two temperatures $T_1$ and $T_2$ and
two normalization factors, which are usually expressed in terms of the volume
emission measures $EM_1$ and $EM_2$ (we assume for simplicity here that the hy-
drogen column density $N_H$ is fixed and that elemental abundances are solar).
Analysis of *Einstein*, *EXOSAT* and *ROSAT* spectra of moderate resolution show
that 1-T and 2-T models provide an adequate fit of the data (in terms of $\chi^2$
statistics) and that 2-T models are invariably needed whenever we have data of
sufficiently high S/N (e.g. Schmitt et al. 1990, Dempsey et al. 1993, Singh et al.
1996). The low-temperature component typically ranges from a few to several
million degrees whereas the high-temperature component is often at tempera-
ture higher than $\sim 10^7$ K. More active stars (like RS CVn binaries and young
rapidly rotating stars) are usually hotter than inactive stars, and giants tend to
be hotter than main-sequence stars of the same spectral type. There is, however,
a large range of possible temperature distributions, as indicated by the different
emission measure ratios observed in stars of different ages, rotation rates and
activity levels (Güdel et al. 1997).

The two well separated temperatures observed in RS CVn binaries and
other active stars (which constitute so far the bulk of the available high quality
spectra) may suggest at first sight that we are dealing with two different families
of coronal loops, one at relatively low temperature and the other at higher tem-
perature. Early observations of eclipsing binary systems, such as those obtained
by *EXOSAT*, gave some support to this interpretation showing that the high-
temperature component was much more extended than the low-temperature one
(e.g. White et al. 1990; we now know, however, that the interpretation of eclipse
data is not so straightforward and that unique solutions are usually not obtained,
 cf. Siarkowski et al. 1996). The two well-separated peaks usually obtained in
the derivation of differential emission measure distributions from high-resolution
data (Mewe et al. 1996) tend to support this concept. On the other hand, the
two temperatures derived by using different instruments were often substantially
different, suggesting some dependence on the detector spectral response and the
existence of a continuous emission measure distribution. In many cases, the ob-
served spectra could be equally well fitted by either a 2-T model and a power-law
differential emission measure model, which mimics the temperature distribution
inside a coronal loop (Preibisch 1997). At any rate, the interpretation of the 2-T fits in terms of a physically meaningful model remains problematic.

A more satisfactory approach is to fit the observed spectra with realistic loop models which, if successful, can provide physical information on loop structures and heating mechanisms. Spatially resolved observations of the Sun show that the solar corona consists of an ensemble of magnetically confined loop-like structures, with different lengths, pressures and temperatures. Thus, the relevant questions are: can a single average loop-like structure, or a small numbers of different families of loops, give integrated spectra which are similar to those observed from stellar coronae? Can 2-T models fit the spectra of coronae formed by only one family of loops, or do we need necessarily two families of loops to reproduce spectra compatible with 2-T fits? Can we discriminate from high-quality spectra between 2-T isothermal models and loop models? What physical information can we derive on coronal structures and hence on the coronal heating mechanisms for stars of different ages, spectral types, rotations and ages? These questions are still far from being solved but are starting to be tackled by current modelling efforts.

We understand quite well the physics of a single magnetically confined loop in hydrostatic equilibrium and energy balance. Its temperature and density structure is determined by a balance between the heating by some magnetic process and the radiative and conductive losses. For the simplified case of constant heating along the loop and constant loop cross-section, this leads to simple scaling laws which relate the maximum temperature $T_{\text{max}}$ at the loop apex, the loop semi-length $L$, the pressure $p_o$ at the loop base and the heating per unit volume $E_H$ (Rosner et al. 1978, Serio et al. 1981). These read (in c.g.s. units):

$$T_{\text{max}} \sim 1.4 \times 10^5 (p_o L)^{1/3} \exp (-0.04 L / s_p)$$

(1)

$$E_H \sim 1.0 \times 10^5 (p_o)^{7/6} L^{-5/6} \exp (-0.5 L / s_p)$$

(2)

where $s_p \sim 5 \times 10^3 T_{\text{max}} g_{\odot} / g_s$ is the pressure scale-height at the loop top. For a loop much shorter than the pressure scale-height, $T_{\text{max}}$ depends only on the product $p_o L$ (and not separately on $p_o$ and $L$), whereas the heating rate $E_H$ is uniquely determined once two of the three quantities $L$, $p_o$ and $T_{\text{max}}$ are fixed.

For a spatially unresolved stellar corona, the total coronal emission will result from the integrated contribution of all loops. In the simplest case that only one type of loops dominates (this is at variance with the solar case, but can be justified if, for instance, the integrated emission is dominated by active regions loops, all with similar lengths and pressures), the total X-ray luminosity will scale as

$$L_X \sim \frac{p_o^2}{T^2} \Lambda(T) L f R_s^2$$

(3)

where $\Lambda(T)$ is the radiative loss function in the X-ray band, $T$ is an effective temperature averaged along the loop (similar to the one provided by 1-T fits of observed spectra), and $f$ is the fractional area of the stellar surface covered by the loop foot-points. If we combine Eq. (1) and (3) above, taking into account that the "effective" temperature $T$ is related to the maximum temperature $T_{\text{max}}$ at the loop apex, it is easy to see that the observed coronal emission (and its
Figure 1. Loop modelling of Procyon (from Maggio & Peres 1997).

spectral shape) will depend on three of the above four parameters, e.g. $T_{\text{max}}$, $p_o$ (or equivalently $L$), and $f$ (with $f \leq 1$). In fact,

$$L_X \sim T \Lambda(T)p_o f$$

where $\Lambda(T)$ is a known function of $T$ ($\sim T^{-1/2}$ in the range of temperatures typical of stellar coronae). Fits of observed spectral data will allow us to constrain $T_{\text{max}}$ (from the shape of the spectrum) and the product $p_o f$ (from the normalization factor (in much the same way as for 1-T models), but they will put little constraint on $p_o$, $L$ and $f$ separately. This is a fundamental limitation of loop models for loops much smaller than the pressure scale height. Additional independent information are needed in order to determine the individual loop model parameters. One possibility is to have loops comparable to the pressure scale height (for which $L \sim s_p$); the other is to have an independent estimate of density (and hence of $p_o$) from density sensitive line ratios.

The above considerations are sustained by extensive loop modelling of stellar coronal spectra (Maggio & Peres 1996, 1997; Ciaravella et al. 1996, 1997; Ventura et al. 1998) using both simulated spectra (generated from loop models) and fitting of real spectra (mostly from the ROSAT PSPC). 1-loop and 2-loop models have been used, as well the usual 1-T and 2-T isothermal fits. The simulations show that in some cases (typically when the ratio of the hot to cool component $EM_2/EM_1 > 1$) 2-T models can fit spectra generated with a 1-loop model, indicating the 2-T models are not necessarily a proof of the existence in stellar coronae of two distinct families of loops (a similar conclusion is implied by the equivalence in many cases of 2-T fits and of fits obtained by using a $\sim T^\alpha$ differential emission measure distribution, Preibisch 1997). On the contrary, when the ratio $EM_2/EM_1$ given by 2-T fits is less than 1, a 1-loop model is usually unable to fit the observed spectra for realistic values of $L$, and a 2-loop model is required. The latter model requires 6 free parameters, i.e. two temperatures $T$, two loop lengths $L$ (or equivalently two base pressure $p_o$) and two filling factors $f$, with the constraint that $f_1 + f_2 \leq 1$. The interpretation of the 6-dimensional parameter space in order to determine confidence regions becomes exceedingly complex in this case, even keeping fixed other parameters.
Figure 2. Loop modelling of ι Vir (from Maggio & Peres 1997).

(e.g. elemental abundances). As for 1-loop models, it is usually not possible to constrain effectively all individual parameters, albeit some useful constraints can be obtained in some cases and for high-quality spectra.

When a 1-loop model is able to fit the data, and the loops are shorter than the pressure scale-height, (as occurred for the ROSAT spectrum of Procyon, cf. Figure 1 from Maggio & Peres 1997, or for the young stars HD283572 and Hz739, Maggio et al. 1997, and for η Boo, Ventura et al. 1998), $T_{max}$ is well constrained by the shape of the spectrum, but $L$, $p_0$ and $f$ are not. Only an upper limit to $L$ (and a lower limit to $p_0$) can be determined by imposing the condition that $f \leq 1$. On the contrary, when the length of the loop is comparable with the pressure scale-height (as occurred for ι Vir in Maggio & Peres 1997, cf. Figure 2), the confidence regions are closed and one can constrain all loop parameters. For loops much larger than the pressure scale height (as for the 1-loop model solutions shown to be unphysical for most G-type stars by Ventura et al. 1998), only $p_0$ is well constrained, while only lower limits can be obtained for $L$ and $T_{max}$.

When a 1-loop model fails to fit the observed spectrum (as for HD3625 in Maggio & Peres 1997 or for most of the G-type stars in Ventura et al. 1998), a 2-loop model provides an acceptable fit. Two distinct families of loops are definitely needed in this case. Only the temperature is well constrained (particularly the lower one in the case of ROSAT), while the loop lengths and pressures are usually not constrained, albeit the range of acceptable 2-loop solutions can be considerably reduced by imposing that the total filling factor $f_1 + f_2 \leq 1$, and thus determining lower limits to $L$ and upper limits to $p_0$ for both families of loops. A more detailed interpretation of the solutions in terms of physical models requires a careful inspection of appropriate multi-dimensional representations of the parameter space (Maggio & Peres 1997, Ventura et al. 1998).

The models run so far suggest the existence in many stars of at least two distinct families of bright loops, one with a temperature of a few million degrees and moderately high pressures (from $\sim 1$ to $10^2$ dyn cm$^{-2}$), covering a significant fraction of the stellar surface, and the other with both higher temperature ($T_{max} \sim 1-3 \times 10^7$ K) and higher pressure ($\sim 10^2$ to $10^4$ dyn cm$^{-2}$), covering only
a few percent of the star. These results give us a first glimpse of the diagnostic potentials of loop models and should be considered as preliminary at this stage. They are based on ROSAT PSPC spectra of moderate resolution and limited bandwidth, and on the assumption of solar abundances. It would be interesting to see the results of loop modelling for instruments with higher resolution and/or larger bandwidth (such as those on ASCA and BeppoSAX or to be flown on AXAF, XMM and ASTRO-E), taking also into account the possibility of non-solar abundances. It can be expected that data with better resolution, larger bandwidth and higher S/N may ultimately lead to discrimination, in terms of \( \chi^2 \) statistics, between 2-T isothermal models and more physically sound loop models. First attempts in this direction using BeppoSAX data (e.g. Sciortino et al. 1998) look promising.

4. Modelling of Stellar Flares

Flare-like brightenings similar to those observed from the Sun but on a much larger energy scale are observed from a variety of late-type stars, including UV Ceti flare stars, RS CVn and Algol type binaries, and PMS stars (e.g. Pallavicini et al. 1990; Ottmann & Schmitt 1994, 1996; Stern et al. 1992; Pallavicini & Tagliaferri 1998a,b). These events are believed to occur via magnetic reconnection, either in magnetically-confined loop-like structures (as in solar compact events) or in the relaxation of an open magnetic configuration to a closed one (as in solar two-ribbon flares). X-ray observations of flares have been discussed by a number of authors and the modelling of flares has been reviewed by Schmitt (1994), Pallavicini (1995) and van den Oord (this volume). Here I will consider only recent advances in the hydrodynamic modelling of stellar flares, while referring to the above reviews for a more comprehensive discussion of previous modelling efforts.

The simplest way to model spatially unresolved observations of stellar flares is by comparing the observed decay time to the characteristic times for radiative \( (\tau_R) \) and conductive \( (\tau_C) \) cooling. Assuming that the flare occurs in a single loop, and that radiative and conductive cooling times are approximately equal, it is possible to estimate the density \( n \), volume \( V \), loop semi-length \( L \) and minimum magnetic field strength \( B_{min} \) from the light curve decay time and the observed values of temperature \( T \) and volume emission measure \( EM \) (derived from spectral fits of X-ray data). This is possible provided there is no appreciable heating during the decay time. Although this may be a plausible assumption for short-lived impulsive flares, it is likely to be completely wrong for intense long-duration events for which the long time scale of the flare suggests prolonged heating in the decay phase. As discussed by Schmitt (1994) and Pallavicini (1995), these cases can be tackled by either a quasi-static cooling model (which approximates the flare decay as a succession of static loop models, van den Oord & Mewe 1989) or by the reconnection model of Poletto et al. (1989), in which heating in the decay phase is provided by the gradual reconnection of an open magnetic field configuration which relaxes to a closed one. Both models are able to reproduce the observed light curve of the flare and can provide plausible values for the relevant physical parameters. Unfortunately, they reproduce the same data sets under completely different assumptions and do not constrain the
flare parameters in a unique way. Not only is the reconnection model unable to discriminate between a small region with high magnetic field strength and a large region with a lower value of the field; it cannot also be distinguished (in its ability to fit real data) from the quasi-static cooling model, thus raising strong doubts about the reliability of the derived flare parameters. For instance, a long duration flare observed by ROSAT from EV Lac could be modelled equally well with the quasi-static cooling model and with the reconnection model, but the inferred size of the region was orders of magnitude different in the two cases (Schmitt 1994).

For flares which occur in magnetically confined loops, the best way to get information on flare loop sizes and energy release is to use full hydrodynamic models which predict the time behaviour of temperature, density and flow velocity in the loop, under the action of a prescribed heating perturbation (e.g. Reale et al. 1988, Cheng & Pallavicini 1991). This is a complex and rather time consuming job which requires the run of a large number of time-dependent simulations for a variety of loop geometries, preflare conditions and energy release rates. Reale et al. (1997) and Reale & Micela (1998) have shown that this approach can be considerably simplified for the flare decay phase by using a semi-analytical expression which relates the flare loop semi-length, the observed light curve decay time \(\tau_{LC}\), the maximum temperature \(T_{\text{max}}\) at the beginning of the flare decay phase, and the slope \(\zeta\) of the temperature vs. density (or equivalently of the temperature vs. \(\sqrt{EM}\)) trajectory during the flare decay. The slope \(\zeta\) is itself related to the time scale of the heating during the decay phase (Jakimiec et al. 1992), a large value of \(\zeta\) corresponding to negligible heating during the decay phase, whereas smaller and smaller values of \(\zeta\) correspond to increasingly longer time scales \(\tau_H\) for heating during the flare decay. In formulae:

\[
L = 2.7 \times 10^3 \frac{\tau_{LC} \sqrt{T_{\text{max}}}}{F(\zeta)}
\]

where \(L\) is the loop semilength and the function \(F(\zeta) = \tau_{LC}/\tau_{th}\) is an empirical fitting to the results of flare loop simulations for a variety of different physical conditions (two different fits are required for loops much smaller than the pressure scale height and for loops comparable to, or larger than the pressure scale height). \(F(\zeta)\) describes the variation with \(\zeta\) of the flare light curve decay time \(\tau_{LC}\) normalized to the spontaneous loop decay time \(\tau_{th} = 3.7 \times 10^4 L/\sqrt{T_{\text{max}}}\). The latter is a characteristic time for the decay of a loop by radiation and conduction, once the heating term has been switched off (Serio et al. 1991).

The method has been extensively tested on solar flares observed by the SXT on Yohkoh (Reale et al. 1997) and has been shown to reproduce quite accurately the lengths of flaring loops (which, in the solar case, can be directly observed). It has also been applied to flares observed by ROSAT (Reale & Micela 1998) and ASCA (Ortolani et al. 1998), providing estimates of the loop length and of the heating duration during the decay. The advantage of this method is that it uses only observable quantities (the flare decay time and the temperature and volume emission measure at different times during the decay) which can easily be extracted from the data, provided these are of sufficiently good quality. The disadvantage, and limitations, of the method is that it relies on the determination of the function \(F(\zeta)\) through a fitting of flare loop model
Figure 3. MECS light curve of a BeppoSAX observation of AB Doradus on November 29-30, 1997 (from Pallavicini & Tagliaferri 1998b).

...simulations folded through the response of the X-ray instrument used. This introduces some scatter, which ultimately limits the accuracy of loop length determinations, and requires that appropriate numerical expressions for $F(\zeta)$ are computed for each X-ray instrument. In addition, the detailed physics of the hydro-simulations remains somewhat hidden in the numerical computations, making the interpretation of the relevant quantities not immediately evident. In spite of these limitations, the method appears promising as a short-cut to detailed modelling of flares with hydrocodes.

Preliminary applications of the method to flares on the dMe stars AD Leo and CN Leo (Reale & Micela 1998) and of the young star AB Dor (Ortolani et al. 1998) show that the derived loop lengths are substantially shorter than inferred by simply equating $\tau_{LC}$ to some characteristic decay time like $\tau_{th}$ or $\tau_R$. This is due to the fact that allowance is made of possible heating during the decay. The duration of the heating supply determines the slope $\zeta$ of the temperature vs. density trajectory as the flare cools down (Jakimiec et al. 1992). In practice, since the density cannot usually be determined from current data, use is made of the temperature $T$ and of the volume emission measure $EM$, which can easily be determined from fits of spectral data (the slope will be the same in a $logT$ vs. $log\sqrt{EM}$ plot). For spectral data of lower statistics, the observed count rate and a sort of spectral hardness ratio can also be used (Reale & Micela 1998). Note that $T_{max}$ that enters Eq.(5) is the flare maximum temperature at the loop apex, which is somewhat higher (by an amount which can be estimated) than the observed maximum temperature at the flare peak (which is averaged over the loop temperature distribution and the instrument spectral response).
5. Hard X-ray Emission from Stellar Flares

I conclude this review of theoretical problems in stellar coronal physics by reporting on a new important observational result obtained recently by the Italian-Dutch satellite BeppoSAX. This is the first detection from stars other than the Sun of hard (>20 keV) X-ray emission during large flares (Pallavicini et al. 1998, Favata 1998). This emission, extending up to ~50 keV, has been detected by the PDS instrument onboard BeppoSAX during the rise phase and at the peak of large flares on Algol (Favata 1998), UX Ari (Pallavicini & Tagliaferri 1998a) and AB Dor (Pallavicini & Tagliaferri 1998b; cf. Figure 3). The emission appears to be thermal and due to a plasma at ~10^8 K. Such high temperatures are required to fit the low energy part of the spectrum, between 0.1 and 10 keV, observed with the LECS and MECS instruments. If this thermal emission is extrapolated to higher energies it accounts fairly well for the hard tail observed by the PDS (Figure 4). There is no need therefore to invoke a non-thermal power-law component as observed during the impulsive phase of solar flares. Moreover, while in solar flares, the hard X-ray emission is much smaller than the soft one (typically ~10^{-5}), the hard tail seen by the PDS is about one tenth of the soft X-ray emission observed at the peak of the flare.

Hard X-ray emission from stellar flares is not unexpected on theoretical grounds, albeit realistic estimates based on the solar analogy makes its detection extremely unlikely (a detector several square kilometers in size would be required if this emission were similar to that observed in solar flares!). This emission is expected to originate from non-thermal bremsstrahlung of high-energy electrons accelerated during the impulsive phase of flares. The electrons are channeled by the magnetic fields and lose their energy as they impinge on the denser chromospheric layers at the loop footpoints. Study of this component provides essential information on the flare primary energy release and particle acceleration. So far hard (> 20 keV) X-ray emission had never been observed.
from stellar flares. The high sensitivity and wide spectral response of BeppoSAX has made this detection possible, but the preliminary analysis of the data shows that the observed emission is most likely thermal and much more intense that would be expected from the scaled-up solar case. If this is confirmed, this hard energy tail will provide additional information on the high temperature component of stellar flares, but will give little information on the primary energy release and particle acceleration. For the latter, we must rely on optical continuum emission as a proxy, unless the ratio of non-thermal hard X-ray emission to thermal soft X-ray emission in stellar flares is orders of magnitude larger than in solar flares. There is no indication for this in the recent detection of stellar hard X-rays by BeppoSAX.

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