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Are Coronae of Magnetically Active Stars Heated by Flares?

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ABSTRACT

Coronal flares are promising candidates as agents for plasma heating in quiescent coronae of magnetically active stars. This letter confronts recently reconstructed coronal emission measure distributions of solar-like stars with results from a statistical, hydrodynamical approach to flare simulations. The time evolution of a statistical set of flare energy release events, distributed in total energy as a power-law as observed in the Sun or in active stars, is simulated in a family of magnetically rigid loops. The resulting time-averaged emission measure distribution is double-peaked with the hotter peak due to the cooling plasma of energetic flares in the larger loops, while the cooler peak can be understood as a dispersion effect of a “quiescent”, isothermal plasma induced by the large number of low-energy flares (microflares). The intervening minimum occurs around 10 MK and can be explained as due to the combined effects of the flare decay of energetic flares, the power-law increase of the flare frequency toward low-energy flares, and a nearly exponential dependence between flare peak emission measure and simultaneous temperature in a given loop. The required simulation flare frequency decreases with decreasing average coronal temperature, in agreement with the observation that the average coronal temperature is correlated with magnetic activity indicators.

Subject headings: stars: activity — stars: coronae — stars: flare — X-rays: stars

1. Introduction

The dominant mechanisms that nature chose to heat solar or stellar coronae still remain unidentified. X-ray observations have indicated that the “quiescent” coronae of magnetically active stars tend to be hotter than coronae of low-activity analogs (e.g., Schrijver, Mewe, & Walter 1984; Schmitt et al. 1990; Schmitt, Fleming, & Giampapa 1995; Jordan & Montesinos 1991; Gagné, Caillault, & Stauffer 1995; Güdel, Guinan, & Skinner 1997a). In rapidly rotating stars, coronal temperatures (T) become comparable to solar flare temperatures. The heating mechanism appears to energize the plasma in such a way that the resulting quiescent coronal emission measure (EM) distribution extends between a few and a few tens of MK, and quite often the EM distribution has

been found to be double-peaked (e.g., Lemen et al. 1989; Dupree et al. 1993; Schrijver et al. 1995; Mewe et al. 1996; Güdel et al. 1997ab).

The phenomenological similarity between the hotter quiescent stellar X-ray emission and solar flare X radiation has provoked a number of studies to propose that a superposition of unresolved flare events may be the cause for the enhanced, quiescent stellar coronal activity (Lemen et al. 1989; Giampapa et al. 1996). In support of this picture, Doyle & Butler (1985) and Skumanich (1985) note that the quiescent coronal X-ray luminosity of active stars, L_X , is correlated with their time-averaged U-band flare luminosity. Benz & Güdel (1994) find a correlation between L_X and the gyrosynchrotron radio luminosity, L_R , that is very similar in quiescent active stars and in solar flares. The observation of steady, non-thermal radio emission due to accelerated electrons in coronal magnetic fields provides itself evidence for frequent acceleration (and therefore probably flaring) events that may release the energy required to explain the correlated L_X (Güdel & Benz 1993).

The frequent-flaring hypothesis, sometimes subsumed in the “microflare” or “nanoflare” picture (Parker 1988), has gained further momentum from the identification of line broadenings in transition-region emission lines (Linsky & Wood 1994; Wood et al. 1996), interpreted as due to a large number of transient, explosive events similar to those previously identified in the solar corona (see Dere, Bartoe, & Brueckner 1989). Further, small flare events with energies of the order of $10^{27} - 10^{28}$ ergs have become observable with the Hubble Space Telescope in cool M dwarfs (Robinson et al. 1995). Solar research has itself provided a large body of evidence for numerous small-scale flare events occurring in the solar corona at any time although there is a lively debate on whether they suffice to heat the non-flaring corona (Lin et al. 1984; Porter et al. 1995; Gary, Hartl, & Shimizu 1997; and others). Kopp & Poletto (1993) present a semianalytical hydrodynamical approach to a nanoflare-heated solar corona to explain the heating of quiet regions. The purpose of the present study is to test to which extent the (micro)flare hypothesis may have merit as a framework to explain the *observed temperature structuring*, i.e., the EM distribution derived from data of recently observed magnetically active solar-type main-sequence stars.

2. Methods

The microflare hypothesis conjectures that a large number of flare events with physical properties that are statistically distributed can describe the observed i) light curve, ii) the distribution of EM in T , and iii) the average radiated luminosity (e.g., L_X). The frequency of solar flares is distributed in energy as a power law: $dN/dE \propto E^{-\alpha}$ with $\alpha \sim 1.8$ typically (Hudson 1991). This seems to apply for stellar soft X-ray flares as well (Collura et al. 1988). I derived the flare FWHM *heating* duration d (the duration of the “impulsive phase”) from a sample of solar microwave flares previously described by Benz & Güdel (1994), complemented by hard X-ray data from Lin et al. (1984) and by HST data of stellar microflares (Robinson et al. 1995), to find a rough correlation with the energy radiated in *soft* X-rays (or the Johnson U band), viz. $d \approx (E_{\text{rad}}/10^{27} \text{ ergs})^{1/2} \times 8 \text{ s}$ with a typical scatter of ± 0.2 dex. A statistical power-law flare frequency distribution with given α

has been constructed using a standard random-number generator. The scatter in d is, for a given total input energy, normally distributed. Each flare is defined by a sinusoidal heating profile of half-duration d with a total energy input E , starting at a random time t within a simulation length of $5 \cdot 10^4$ s.

The notoriously difficult description of the flare hydrodynamics requires a number of simplifications for a statistical approach (Sturrock et al. 1990; Kopp & Poletto 1993; Cargill 1994). I apply here an approach proposed by Kopp & Poletto (1993) for solar coronal quiet regions that essentially averages the loop properties over volume and therefore reduces the problem to a system of two hydrodynamical differential equations that describe a “zero-dimensional” loop with the properties of temperature T , density n , and average flow velocity; losses occur via conduction and thermal radiation. The approach is sufficient for our purpose since the formalism reproduces the phenomenology of sophisticated flare simulations quite well (Kopp & Poletto 1993). I refer to their paper for a description of the equations. Here, the main purpose is a confrontation with results from recent stellar observations. The hydrodynamics has been reformulated for a typical hydrogen-helium plasma (abundance ratio 10:1, pressure $p = 1.92n_e kT$).

The simulation system consists of a number of semi-circular loops, each with constant cross section along its length. The loop semi-length (footpoint to apex, L) was kept as a fixed parameter for a simulation while the volume was varied by varying the cross-sectional radii among the loops. The loop radii are uniformly distributed between two specific values $r_{\min}$ and $r_{\max}$. The value of $r_{\max}$ is bounded by $\approx 1.6L$ in the present simulations. Although too large for the geometry of a single semi-circular loop, such large r describe a volume equivalent to a system of connected loops involved in the flare. The minimum loop radius $r_{\min}$ was set to a value that ensures that the smallest loop can be loaded at least with the lowest-energy flares. This geometry imposes a limitation on the total number of loops since the total cross-sectional area of all loops must not exceed the stellar surface area.

In assigning each flare randomly to one of the loops, the range of allowed loops was limited by a lower bound $r_{\lim}$ to the acceptable loop radius r , $r_{\min} \leq r_{\lim} \leq r_{\max}$, such that the magnetic energy of the loop exceeded the total flare energy. This avoids significant evolution of the loop geometry (which would introduce a number of additional free parameters and would lead beyond easily tractable hydrodynamic conditions). The loop is thus assumed to be rigid. As a consequence, the smallest loops were loaded with low-energy and thus very short flares only. Their impulsiveness leads to very rapid heating to extreme T before a significant amount of plasma enters into the loop through chromospheric evaporation. In these cases, an upper limit was imposed on the volumetric heating rate (and thus again a lower limit for the allowed r), essentially keeping the flare peak T below 100 MK. This second criterion is, however, only important for the smaller loops which contribute a minor portion of the total EM. The most energetic flares in the tail of the power-law distribution could be dropped if their energies exceeded the magnetic energy of the largest loop. The number of flagged flares had to be negligible (typically ≤ 3 outliers in a 50 ks simulation) in order to keep statistical confidence.

The system was initialized by assuming hydrostatic equilibrium (quiet loops). I decided for an equilibrium T_0 at the lower end of the T range identified in ASCA data. The equilibrium density then follows from a relation given by Rosner, Tucker, & Vaiana (1978) for hydrostatic loops. The present modeling does not address the equilibrium heating of these low-density, cool initial loops.

The free parameters are i) the power-law index α , ii) the loop semi-length L , iii) the lower flare-energy cutoff E_0 , iv) the number N of flares for the 50 ks system, v) the (constant) loop magnetic field strength B , and vi) the number of loops. Clearly, N and E_0 are related for a given α since reducing E_0 with the same N implies a reduction of the number of *energetic* flares. Therefore, E_0 was kept constant at 10^{27} erg in all simulations.

3. Discussion of Results

I extracted the integrated total EM distribution from the simulation by binning the instantaneous EMs in each loop in T and averaging over all loops and in time. Similarly, the light curve is the summation of all simulated X-ray losses of each loop.¹

Figures 1 and 2 compare observed EM distributions from ASCA spectroscopy of young, active solar-type G stars (from Güdel et al. 1997a) with select simulations; the (non-unique) parameters use here are summarized in Table 1. The simulation results are compatible with the observed EM distribution, the observed L_X , and the observed light curve characteristics. (The remaining discrepancies in the EM distribution are hardly significant; the observational reconstruction is subject to method-inherent systematic effects, see Güdel et al. 1997b.) Relatively compact loops with $L = 4 \cdot 10^9$ cm were chosen to comply with the surface filling limitation (complete filling for EK Dra) since longer loops have a lower equilibrium density ($n_{e,0} \propto L^{-1}$) for a given T and produce EM less efficiently (in equilibrium, $EM_0 \propto n_{e,0}^2 V \propto L^{-1}$) despite their proportionately larger volume. For HN Peg, two flares had to be eliminated for their excessively large energies, while none required flagging for the other two stars. The large B for EK Dra is justified since the large filling with loops prevents a large divergence of B . It also nicely reproduces the shift of the hot EM bump toward higher T than in the case of HN Peg. Although the hot EM bump is produced by the minority of strong flares, their number is sufficiently large to clearly reproduce the EM shape with different initializations of the random number generator. The singular largest flare contributes only 10% to the maximum bin of the hotter EM distribution of EK Dra, and 6.5% in HN Peg’s case.

By varying the free parameters, the following systematics are found: i) The resulting EM distributions are bi-modal with maxima just above T_0 and between 15–50 MK. Depending on

¹Note that the X-ray losses are not identical to the *total radiative losses* used in the simulation which include losses at much lower and higher photon energies as well. The total loss function and the X-ray loss function were derived from the XSPEC software vers. 9.0 using its MEKAL code with solar abundances. Also note that the simulation EM was divided by 2 to compare with the *observed* EM from the visible hemisphere. Similarly, only $\approx 50\%$ of the total X-ray losses of each portion of EM contributes to the star’s L_X if X-ray backheating to high T is neglected.

the choice of parameters, one of the bumps can disappear. There is usually a local minimum around 10 MK. ii) The hotter part of the EM distribution becomes more significant for harder flare distributions (smaller α), or for more numerous flares (with constant E_0). iii) For longer loops, the hotter EM part becomes less important for otherwise identical parameters. iv) The light curve shows a slow modulation with relative amplitudes of the order of 10–30%. v) The peak T of the hotter EM bump becomes higher for stronger B . I now discuss these points and their relevance for the observations.

In the simulations, the minority of the higher-energy events heats the loops to high T ; since large flares have to occur in reasonably large loops, chromospheric evaporation leads to a significant increase of the electron density and hence to large EM contributions. As the flares decay from their peaks, T first recedes, and then the EM begins to drop as well due to condensation of cooling material. Recently, Feldman, Laming, & Doschek (1995) found that the peak EM of solar and stellar flares is to a rather good approximation an *exponential* function of the simultaneous T . This relation is indeed also recovered from our simulation system within a given loop geometry. The double-peak structure has thus the following qualitative explanation in the framework of the flare-heating hypothesis: The high- T bump is due to a moderate number of strong flares, with the exponential function $\text{EM}_{\text{peak}}(T)$ outweighing the power-law decrease in their frequency. The low- T bump, on the contrary, is dominated by the large number of small flares that heat the “quiescent” plasma only weakly and therefore “disperse” the quiet plasma. The intervening local minimum in EM is a consequence of the decreasing inverse power-law for the flare frequency, and the increasing exponential function $\text{EM}_{\text{peak}}(T)$. Discrepancies between simulations and observations are hardly surprising in the light of the limited accuracy of the EM reconstructions, the crude geometric model, and the rather artificial assumption of one fixed T_0 for all loops. The model could be extended such that a still larger number of smaller flares (“nanoflares”) heat the loops from a cooler T to our T_0 , but a discussion of the nature of the low- T plasma is beyond the scope of this Letter.

If a larger number of energetic flares are included (smaller α or larger flare frequency), the hot bump reacts sensitively and increases its EM. On the other hand, longer loops start with a lower initial density, induce less chromospheric evaporation due to a smaller temperature gradient, and reach lower-density peaks resulting in smaller high- T EM contributions. Larger loop radii are required for more energetic flares. Therefore, if B is increased, higher-energy flares can be accepted by a given loop of given initial density, so that impulsive heating can reach higher T .

Observations of active stars often show slow variability within a factor of two, apart from obvious flaring (Ambruster et al. 1987; Collura et al. 1988; for specific examples, see also Dorren, Güdel, & Guinan 1994; Güdel et al. 1996). Most of the simulated flare contributions average to a quasi-steady “quiescent” radiation while only the most energetic events define an irregular slow modulation (see also Kopp & Poletto 1993). Its time scale amounts to 0.4–0.8 hrs for EK Dra and 0.3–0.6 hrs for HN Peg and κ^1 Cet, compatible with results in the light curve analyses mentioned above. This points at largest flares with a total radiated energy of $\sim 5 \cdot 10^{30} - 5 \cdot 10^{31}$ ergs in the simulations presented in Figure 2, i.e., comparable to large solar flares.

Although the presented results cannot by themselves provide proof for the occurrence of a large number of flares nor for their role in the heating of active stellar coronae, the simulations together with the increasing evidence from previous observations suggest that a statistical flare heating model may well be a good candidate for the further identification of the primary coronal heating mechanism. This study suggests that the *flare frequency* (above E_0) is a fundamental parameter that decreases with decreasing stellar activity, as might be expected. It controls the average coronal temperature, which has indeed been found to also decrease with decreasing magnetic activity indicators.

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Table 1. SIMULATION PARAMETERS AND RESULTING L_X

Parameter	EK Dra	HN Peg	κ^1 Cet
Number of loops	300	180	100
Number of flares [10^6]	7.5	1.2	1.5
B [G]	800	300	100
α	1.8	1.8	2.0
T_0 [MK]	6.0	4.5	4.5
L_X [10^{28} erg s $^{-1}$]	45	6.6	3.1

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Fig. 1.— Observed EM distributions of three solar-type stars of different ages (from top to bottom: EK Dra, age ≈ 70 Myr; HN Peg, ~ 300 Myr; κ^1 Cet, ~ 750 Myr). The EMs were reconstructed from ASCA data. (From Güdel et al. 1997a.)

Fig. 2.— Statistical simulations of a hydrodynamic loop system. Parameters have been chosen so as to be representative of the observations in Figure 1. See text for details.

Fig. 1

Fig. 2