The Coronae of AD Leo and EV Lac

By S. SCIORTINO[1], A. MAGGIO[1], F. FAVATA[2] AND S. ORLANDO[3]

[1]Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy

[2]Astrophysics Div. – SSD ESA, ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands

[3]Solar System Div. – SSD ESA, ESTEC, Postbus 299, NL-2200 AG Noordwijk, The Netherlands

We present results of the analysis of X-ray observations of the active M dwarfs AD Leo and EV Lac. The PSPC spectra can be fitted with one- (EV Lac) or two-component (AD Leo) isothermal MEKAL models, and very low metallicity ($\sim$ 0.1 solar); during an intence flare the spectrum of EV Lac can be fitted only by adding a second component with log T $\sim$ 7.5. The SAX light-curves of AD Leo and EV Lac also show the occurrence of several flares. The fits of the SAX spectra require at least three thermal MEKAL components and best-fit coronal plasma metallicity below solar for AD Leo and only marginally below solar for EV Lac.

We have also fitted the SAX spectra of AD Leo and EV Lac with model spectra from constant cross-section static coronal loops. One-loop models fail to fit the observed spectra. A second loop component, that accounts for most of the plasma emission at high energy, is required to obtain an acceptable fit. We interpret the fit results as pointing toward the existence of various (at least two) dominant classes of coronal emitting structures: the dominant one is composed of hundreds of compact loops, with lower maximum temperature and length smaller than 0.1 the stellar radius, covering no more than 1% of stellar surface; the second one, responsible for the high energy emission, is composed at least of tens of quite elongated loops, covering a very small fraction of stellar surface.

1. Introduction

Einstein IPC X-ray spectra of solar-type stars, observed with sufficient photon statistics, usually require two emission components from an optically thin plasma to be adeguatelly modeled (cf. Vaiana 1983, Schmitt et al. 1990). In the case of dMe stars the fits usually result in one component at few million degrees, and a second one at few tens million degrees. While the need of two thermal components does not necessarily imply the presence of two distinct emitting "regions" at different temperatures in the stellar coronae, it certainly reflect the presence of a (complex) thermal structure in stellar coronae. This description has been confirmed and extended by the analysis of spectra gathered with the Position Sensitive Proportional Counter (PSPC) on board ROSAT. The recent analysis of ASCA, EUVE and SAX spectra (White 1996; Drake 1996; Favata 1998; Pallavicini 1998 and references therein cited) of several nearby and/or active stars has further reinforced a description of stellar coronal spectra in terms of scaled version of the solar emission.

There are several reasons that makes the study of the coronal emission of dMe stars a worth effort. First of all, their X-ray emission level makes them among the most intense coronal emitters, hence they are a good test-bed for any proposed mechanism for the heating of stellar coronae. Their internal structure, reflected by their cool photospheres, should minimize any contribution by non-magnetic (acoustic) heating processes making easier to pin point the characteristic features of the coronal magnetic heating mechanism (down to the so called micro-flare level) and their relation to any kind of dynamo activity,

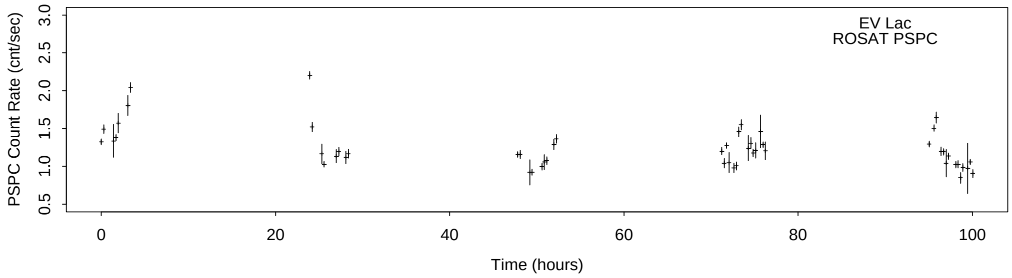

FIGURE 1. PSPC light-curve of EV Lac, accumulated in 1000 sec bin size, obtained combining 5 distinct observations taken in 5 consecutive days. Notice that the data are suggestive of a coronal variability up to a factor 2 over the time scale explored. analyzed.

either based on a scaled version of the solar $\alpha-\omega$ dynamo or on the more elusive turbulent dynamo (cf. Durney et al. 1993) that has been suggested to be at work in the (almost) fully convective late dM stars (Stern et al. 1995).

To gain insight in the above questions we have obtained observations of the active dMe stars AD Leo and EV Lac with the SAX X-ray astronomy satellite.

AD Leo (GJ 388) is a single dM4.5e star at a trigonometric distance of 6.15 pc with an X-ray flux to the Earth $f_X \sim 3\ 10^{-11}$ erg sec^{-1} cm^{-2} (Barbera et al. 1993; Schmitt et al. 1995), EV Lac is a single dM4.5e star at a trigonometric distance of 5.08 pc and $f_X \sim 4\ 10^{-11}$ erg sec^{-1} cm^{-2} (Schmitt et al. 1995). They are both well known flare stars, extensively studied and are known to emit from infrared up to X-rays. Their space velocities make them members of young disk population based on the criterion of Eggen (1973). They are among the few dM stars for which, adopting the Zeeman broadening technique, it has been possible to derive the (mean) value of the surface magnetic field in the spots, with the associated area coverage (Saar 1990). The deduced magnetic fields are of the order of 10^3 Gauss (similar to the intensity of magnetic field in solar spots) with area coverage fraction above 70% (i.e. well above the typical spot coverage in the Sun). This is a clear evidence that some kind of dynamo action should be at work in these almost fully convective stars.

It is worth to note that the IPC spectrum of AD Leo cannot be adequately fitted, for an assumed solar composition of emitting plasma, either with 1-T or 2-T Raymond-Smith plasma emission models, or with a continuous power-law emission measure distribution (Schmitt et al. 1990).

2. The PSPC Observations of AD Leo and EV Lac

There is one single PSPC observation of AD Leo lasting about 27 ksec, while EV Lac has been observed six times with observations of 3 to 7 ksec each.

The entire spectral analysis, including the analysis of SAX spectra of Sect. 3, has been performed using the XSPEC V.10 package and the so-called MEKAL plasma emissivity model. PSPC spectra and light-curves extraction has been performed using PROS V2.4.

2.1. *AD Leo PSPC spectrum*

In order to make easy and more consistent the comparison with the results of the rest of our analysis, based on a different plasma emissivity code, we have re-analyzed the AD Leo PSPC spectrum whose analysis, based on the Raymond-Smith emissivity model (Raymond & Smith 1977, Raymond 1988), has been presented by Giampapa et al. (1996, hereafter G96)). We find that: a) it is impossible to obtain a statistically acceptable two-component fit if we keep fixed the value of hydrogen column density to $N_H = 10^{18}$ cm^{-2} that is within a factor two from the value recently derived by the analysis of an EUVE spectroscopic observation of AD Leo (cf. Cully et al. 1997); b) our analysis based on the MEKAL plasma emissivity model results in higher temperatures (log $T_L = 6.82$, log $T_H = 7.22$) and in $EM_L/EM_H = 5.9$ much greater than the published ones (cf. G96) derived adopting the Raymond-Smith plasma emissivity code. It is worth noting that the individual emission measure EM_L and EM_H obtained with our fit are both significantly lower than those reported by G96 because the MEKAL plasma emissivity per unit emission measure is greater than the one predicted by the Raymond-Smith plasma emissivity.

2.2. *EV Lac PSPC spectra*

Since analysis of the EV Lac PSPC spectra has not been published yet, we have analyzed the available archive data. As a first step we have constructed the PSPC light-curves; for the ROR's from 201583 to 201587 spanning 5 consecutive days, we have constructed a single light curve (cf. Fig. 1) to investigate the presence of intence flares.

Our fit results clearly shows that i) except for the strong flare (ROR 200984), the PSPC spectra of EV Lac can be described by best fit 1-T models with derived parameters (log T $\sim$ 6.8, Emission Meassure $\sim$ 5-7 10^{51} cm^{-3}) that are compatible within the error bars with a single value, ii) a coronal metallicity lower than solar ($Z/Z_\odot \sim 0.1$) is required to obtain good fits in all cases, iii) during the flare an high-temperature component (log T $\sim$ 7.6) has to be added to obtain a best fit, while the low-temperature component remains unchanged; iv) the limited spectral resolution and energy bandpass of the ROSAT PSPC, is unable to well constraint the value of the flare high temperature component.

3. The SAX Observations of AD Leo and EV Lac

The new SAX data where acquired with the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), which covers the energy range 0.1–10 keV with a spectral resolution $\Delta E/E \simeq 20\%$ at 1 keV and scaling as $E^{-1/2}$, and with the Medium Energy Concentrator Spectrometers (MECS's, Boella et al. 1997), which covers the energy range 1.5–10 keV with a spectral resolution $\Delta E/E \simeq 8\%$ at 6 keV and scaling as $E^{-1/2}$. The SAX observation of AD Leo was performed on April 23–34, 1997, and resulted in an effective exposure time of 43.3 ks for the three MECS units, and of 19.6 ks for the LECS†. The SAX observation of EV Lac was performed on December 7–8, 1997, and resulted in an effective exposure time of 33.9 ks for the two MECS‡, and of 9.7 ks for the LECS.

The source spectra were re-binned so to have at least 30 counts per energy bin, and bins with energies below 0.1 and above 7.0 keV were discarded in the case of LECS, while for the MECS spectra we have retained the bins with energies between 1.5 and 7.0 keV.

3.1. *The SAX X-ray Light-Curves*

The AD Leo X-ray light curves, accumulated in 400 sec bins, for the LECS and the three combined MECS detectors are shown in Fig. 2. The LECS light curve shows evidence of variability up to a factor 2 on a time scale of few thousands seconds, associated to the occurrence of flares (and possibly of other low-amplitude variability). The presence of variability is confirmed by the results both of the χ^2 and the Kolmogorov – Smirnov tests, while the same tests confirm that the background is consistent with being constant.

† The LECS exposure time is always significantly shorter than the MECS exposure time, because the LECS was operated during Earth dark time only, at the time of both observations.

‡ In the time separating the two observations one of the three MECS's has developed an unrecoverable problem and has been turned off.

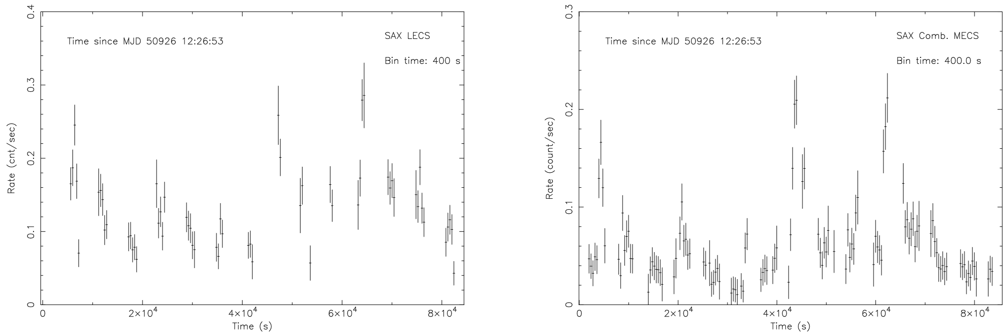

FIGURE 2. (a) [left-panel] The light curve of the SAX/LECS observation of AD Leo accumulated in 400 second bins, shows that the coronal emission level of this star is highly variable. (b) [right-panel] The light curve of AD Leo accumulated in 400 sec bins, from the three combined MECS detectors onboard of SAX. The curve shows the occurrence of flares at about 6, 42, and 60 ks since the beginning of the one day long observation.

The MECS light-curve also shows evidence for intense source variability, again confirmed both by the a simple χ^2 test and a Kolmogorov – Smirnov test. From the inspection of Fig. 2 it is evident the occurrence of, at least, 3 flares during the 1 day long observation. The peak count rates of these flares are $\sim$ 4–5 times higher than the "quiescent" coronal emission level. The overall appearance of LECS and MECS light curves strongly indicates that a large fraction (30-50%) of the overall emitted X-rays occurs in flares.

As for AD Leo the SAX observation of EV Lac spans approximately one day. With the same procedure adopted for AD Leo we find that the background-subtracted LECS and combined MECS light-curves indicate the presence of variability, whose existence has been confirmed by applying the χ^2 and the Kolmogorov-Smirnov tests. The MECS light curve shows two intense flares, occurring respectively 20 and 60 ks since the beginning of the observation, plus some less extreme variability. The decay times of the two flares derived with formal fits are about 4.5 ks and 1.4 ks, respectively.

3.2. *Fit of SAX Spectra*

Given the limited counting statistics of the sources we have jointly fitted the available LECS and MECS spectra assuming a constant normalization among the four detectors fixed in such a way that a source of given flux yields in the LECS 70% of the count-rate in any of the three MECS (that instead are all equivalent).

As demonstrated by an extensive set of simulations presented by fmp+97, LECS spectra allow us to get fair diagnostic capabilities for the global metallicity of coronal plasmas, thanks to the wide spectral coverage. On the contrary the low statistics of the present SAX spectra, together with the spectral resolution above 0.6 keV lower than for the ASCA/SIS, makes unrealistic the analysis with variable individual abundances (as we will show in the following, acceptable fits can be found varying only the global metallicity in the fit).

3.2.1. *The SAX spectra of AD Leo*

We first attempted to fit the available spectra with a 2-T MEKAL model with the global abundance of metals in the emitting plasma, relative to the solar value, left as a free parameter in the fit. This fit yields a value of χ^2 of 185.1 with 145 d.o.f. (probability 1.4%) and does not result in an acceptable model description. In order to obtain an

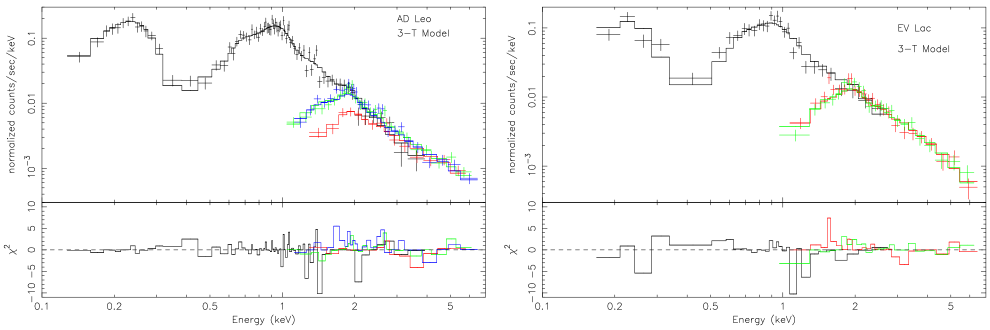

FIGURE 3. [right-panel] The observed SAX spectra of AD Leo together with the best-fit three-temperature MEKAL spectrum, yielding a global metallicity 0.25 times solar. Note that most of improvement of this fit with respect to the 2-T fit occurs in the spectral region around 0.6 keV. [left-panel] The observed SAX spectra of EV Lac together with the best-fit three-temperature MEKAL spectrum, yielding a global metallicity 0.59 times solar. Again note that most of improvement in the 3-T fit occurs in the spectral region around 0.6 keV. Bottom panels y-axis shows the (signed) contribution of each bin to the total χ^2.

acceptable fit we have added a third thermal MEKAL component and have repeated the fit leaving the metallicity free to vary. The resulting best-fit (log $T_1 \sim 6.6$, log $T_2 \sim 7.1$, log $T_3 > 8.13$, with 90% confidence ranges on $Z/Z_{\odot} = 0.22$-0.35) model is shown in Fig. 3. The confidence intervals show that we can only set a lower-limit to the value of the high-temperature. The fit formally converges with a value of χ^2 of 163.0 for 145 d.o.f. corresponding to a probability level of $\sim$ 9.0%. While the value of metallicity is constrained to be lower than solar, available data do not constrain the value of the temperature of the hotter component nor allow us to discriminate between the (assumed) thermal and a non-thermal nature of this hot component.

3.2.2. *The SAX spectra of EV Lac*

We first attempted to fit the available spectra with a 2-T MEKAL model with metallicity left free to vary. This fit yields a value of χ^2 of 103.8 for 78 d.o.f. corresponding only to a probability of 1% to give an adequate description of EV Lac coronal spectrum. In order to improve our model description we have added a third thermal MEKAL component and have repeated the fit leaving the metallicity free to vary. The fit yields a value of χ^2 of 95.2 (for 78 degree of freedom) that corresponds to a null hypothesis probability of 2.9%, i.e. a marginally acceptable fit. The 3-T fit parameters are log $T_1 \sim 6.5$, log $T_2 \sim 6.9$, log $T_3 \sim 7.4$, with 90% confidence ranges on $Z/Z_{\odot} = 0.36$-1.11.

4. Loop Modeling

In view of the complexity of the thermal structure of the coronae of AD Leo and EV Lac, we have attempted to fit the SAX spectra with a model synthesized from constant cross-section static coronal loops (Serio et al. 1981, Ciaravella et al.,1996)). This modeling approach has been recently adopted to fit the PSPC spectra of F and G-type stars (Maggio & Peres 1997, Ventura et al. 1998).

As an extension to the works cited above we have constructed a grid of coronal loop models having as free parameter also the plasma metallicity, beside the loop length, l, and the plasma maximum temperature, T_{max}. This model has as further free parameter the surface filling factor, f, i.e. the fraction of stellar surface covered by a given class of loops.

TABLE 1. Summary of 2-loop model fits of SAX Spectra

Star	Z ($Z/Z_\odot$)	Log(T_{max1}) (K)	Log(l_1/R_*)	f_1	Log(T_{max2}) (K)	Log(l_2/R_*)	f_2	Prob (%)
AD Leo	0.23 [0.20-0.30]	7.12 [7.09-7.14]	-2.3 [< -1.0]	1.6e-4 [<3.1e-3]	8.5 [> 8.2]	-2.1 [unconstr.]	1.0e-10 [unconstr.]	7.3
EV Lac	0.45 [0.32-0.69]	6.90 [6.74-7.01]	-2.3 [<-1.4]	2.1e-4 [<1.7e-4]	7.53 [7.47-7.58]	-2.3 [<-1.2]	9.4e-7 [<1.2e-5]	1.7

1- The reported parameter uncertainty ranges are computed at 90% confidence level assuming a single interesting parameter.
2- Given the small source distance, and the result obtained by Cully et al. (1997), all the AD Leo fits were performed assuming $N_H = 10^{18}$ cm^{-2}.
3- Given the small source distance and the fits of PSPC spectra we have decided to adopt $N_H = 10^{19}$ cm^{-2}. We have checked that no acceptable fit can be obtained with a lower hydrogen column density.

We have found that one-loop model cannot give an adequate description of the observed spectra. We have then added a second loop component to our model obtaining the fitting results shown in Fig. 4 and summarized in Table 1. As a matter of fact the "quality" of the best-fit 2-loop models, as measured by the probability level of the χ^2 test, is better than for the 2-T models, and slightly worse than for the best-fit 3-T models. Note that 3-T models and loop models have the same number of fitted parameters.

In order to properly interpret loop fit results it is necessary to recall that if the loop length is smaller than the pressure scale height, $H = 2kT_{max}/\mu g = 6000 T_{max}/(g/g_\odot)$ (where g is the stellar gravity, and T_{max} is in units of K) the solution of the loop static equations imply the so-called RTV (Rosner et al. 1978) scaling law among T, l and the loop base pressure, p, namely $T_{max} = 1.4\ 10^3 (pl)^{1/3}$.

Our fit results are consistent with loops having lengths much smaller than the pressure scale height, hence RTV scaling law applies. In this case, T_{max} (and hence the product pl) is the only parameter well constrained by the fit, while the other quantities, including the surface filling factor, may take a range of possible values while yielding the same quality of the fitting result. This is an *intrinsic* property of the model and *cannot* be overcome. Moreover, note that the overall X-ray luminosity emitted by a given loop can be expressed as $L_X \sim 2.16\ 10^{16}\ \gamma\ (R_*/R_\odot)^2\ T_{max}^{7/2}\ f\ l^{-1}$ erg/sec, where γ is the fraction of energy input (heating) that is emitted in the X-ray band. Since T_{max} is usually well determined, the overall observed luminosity constrains the quantity f/l; this is the way in which we have estimated the upper limits on f from the upper limits on l, as reported in Table 1. Since T_{max} and lp are related by the scaling laws, the above dependence implies that, for loop lengths shorter than the pressure scale height, l, p and f can occupy a range of admissible solutions (possibly limited also by the constraint $f < 1$). In other words, when $l < H$, the loop modeling cannot provide *one solution*, but instead a range of admissible solutions with different area coverage and base pressure (or length) of the emitting loop. In any case, the above fitting results with loop models allow us to infer some of the properties of the stellar coronae, which could not be otherwise derived.

As a further step in the interpretation of the fitting results, let us consider that the area coverage factor can be written as $f = N\alpha^2\beta^2/4$ where N is the number of loops of a given component, α is the loop aspect ratio, i.e the ratio between loop base radius

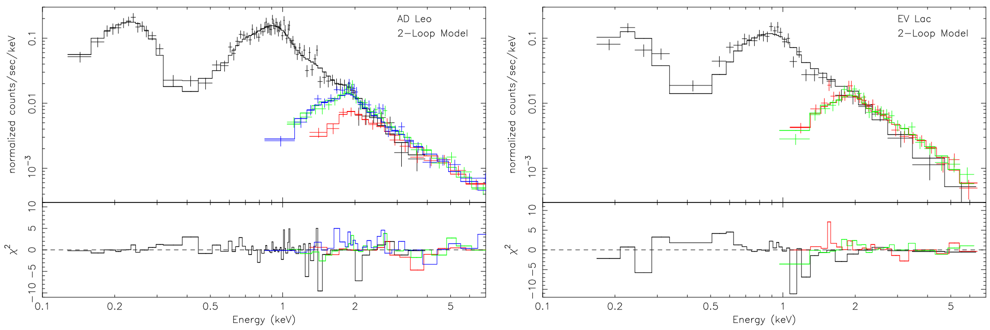

FIGURE 4. [left-panel] The fit of the SAX spectra of AD Leo with a model of emission from a 2 coronal loop plasma model. For this fit the hydrogen column density has been taken fixed to log $N_H = 18$. [right-panel] The fit of the SAX spectra of EV Lac with a model of emission from a 2 coronal loop plasma model. Note that, similarly, to the 3-T fit case, the fit is statistically unsatisfactory mostly because the model does not reproduce the emission below 0.5 keV. For this fit the hydrogen column density has been taken fixed to log $N_H = 19$, however leaving free to vary the value of N_H improves only marginally the fit.

and length†, $\beta = l/R_*$ is the ratio between loop length and stellar radius. For each of the loop components we have derived the values of f and of β, hence we can deduce the value of N as a function of the loop aspect ratio. *Note that f/β is constant within the confidence regions determined by the fitting.*

Let us focus on the AD Leo low-T_{max} loop: in this case our analysis gives a best-fit solution $N\alpha^2 = 4f/\beta^2 \sim 25.5$, and a formal 90% confidence limit which translates in $N\alpha^2 > 1.24$. Hence, for $\alpha \sim 10^{-1}$ we would have a best-fit solution $N \sim 2500$, with a formal 90% confidence limit $N > 124$. Assuming instead the maximum loop aspect ratio, $\alpha = 1/\pi$, we would obtain $N > 12$. We interpret this findings as evidence that the lower T_{max} loops are indeed quite compact with length smaller than 0.1 stellar radius (and smaller than the pressure scale height) and that they cover a fraction not greater than 0.3% of stellar surface with tens to hundreds of loops.

Going to the high-T_{max} loops, we have $N\alpha^2 = 6.3\ 10^{-6}$, with the condition $N \geq 1$, this implies $\alpha \leq 2.5\ 10^{-3}$, i.e. the solution is compatible with elongated and thin loops covering a very small fraction of the stellar surface. While we cannot set a 90% confidence limit on β, hence on the value of α, yet if we assume as possible solution loops with $\alpha \sim 0.1$, i.e. typical solar loops, we can deduce that the loop length should be extremely small, $\leq 10^{-5} R_*$, in order to meet the condition $N > 1$. Similar arguments apply also for EV Lac.

Our findings indicate that the coronae of active dM stars can be described by (at least) two major emitting structures (let say two major loop classes) with well distinct maximum temperatures. The corona of AD Leo is globally "hotter" than the corona of EV Lac. In both stars the loops with the lower T_{max} are compact (aspect ratio < 0.3-1.5), with length smaller than 0.1 stellar radius, base pressure higher than typical solar loops, and area filling factor of 10^{-4}–10^{-3}. There should be, at least, tens-hundreds of such loops to explain the observed emission. The higher T_{max} loops tend to have a more elongated structure (aspect ratio in the 10^{-1}–10^{-3} range), while maintaining a length smaller than 0.1 stellar radius. Because their area coverage factor is quite small,

† For the given loop geometry, we have the constraint $\alpha < 1/\pi \sim 0.32$ to avoid overlap of the loop foot-points

only at most ten of them are contemporary present in the corona. Given their elongated structure we argue that their base pressure is even higher than the pressure of the lower T_{max} loops, and they are likely to be non-steady and continuously replenished in the corona. This picture is consistent with that derived from the analysis of AD Leo PSPC data (Giampapa et al. 1996).

While we have not done detailed analysis of any specific flare, yet our results seem to contradict the existence of AD Leo loops with length comparable to the stellar radius (Cully et al. 1997), while it is more consistent with the recent analysis of the AD Leo flare seen with the ROSAT PSPC that has been interpreted as occurring on a loop whose length was of the order of 0.1 stellar radius (Reale & Micela 1998).

SS, and AM acknowledge partial support from ASI and MURST.

REFERENCES

Barbera M., Micela S., Sciortino S., Harnden, F.R. J., Rosner R. 1993, *ApJ* **414**, 846

Boella G., Chiappetti L., Conti G. et al. 1997, *A&AS* **122**, 327

Ciaravella A., Peres G., Maggio A., Serio S. 1996, *A&A* **306**, 553

Cully S., Fisher G., Hawley S. L., Simon T. 1997, *ApJ* **491**, 910

Drake J. U. 1996, in R. Pallavicini, A. Dupree (eds.), Cool Stars, Stellar Systems, and the Sun. Ninth Cambridge Workshop, Vol. 109 of *ASP Conf. Series*, ASP, 203

Durney B. R., De Young D., Roxeburg I. W. 1993, *Solar Phys.* **145**, 207

Favata F. 1998, in R. A. Donahue, J. A. Bookbinder (eds.), Cool Stars, Stellar Systems, and the Sun. 10th Cambridge Workshop, Vol. in press

Favata F., Maggio A., Peres G., Sciortino S. 1997, *A&A* **326**, 101

Giampapa M. S., Rosner R., Kashyap V., Fleming T. A., Schmitt J. H. M. M. 1996, *ApJ* **463**, 707

Maggio A., Peres G. 1997, *A&A* **325**, 237

Pallavicini R. 1998, in L. Scarsi, H. Bradt, P. Giommi,, F. Fiore (eds.), The Active X-ray Sky: Results from BeppoSAX and Rossi-XTE, Vol. in press

Parmar A. N., Martin D. D. E., Bavdaz M. et al. 1997, *A&AS* **122**, 1

Raymond J. 1988, in R. Pallavicini (ed.), Hot thin plasmas in Astrophysics, Kluwer, Dorderecht

Raymond J., Smith B. 1977, *ApJS* **35**, 419

Reale F., Micela G. 1998, *A&A* **334**, 1028

Rosner R., Tucker W. H., Vaiana, G. S. 1978, *ApJ* **220**, 643

Saar S. H. 1990, in J. O. Stenflo (ed.), Solar Photosphere: Structure, Convection and Magnetic Fields, Kluwer, Dorderecht, 427

Schmitt J. H. M. M., Collura A., Sciortino S. et al. 1990, *ApJ* **365**, 704

Schmitt J. H. M. M., Fleming T. A., Giampapa M. S. 1995, *ApJ* **450**, 392

Serio S., Peres G., Vaiana G. S., Golub L., Rosner R. 1981, *ApJ* **243**, 288

Stern R., Schmitt J., Kahabka P. 1995, *ApJ* **448**, 683

Vaiana G. S. 1983, in O. Stenflo (ed.), Solar and Stellar Magnetic Fields: Origins and Coronal Effects, Reidel, Dorderecht, 165

Ventura R., Maggio A., Peres G. 1998, *A&A*, in press,

White N. E. 1996, in R. Pallavicini, A. Dupree (eds.), Cool Stars, Stellar Systems, and the Sun. Ninth Cambridge Workshop, Vol. 109 of *ASP Conf. Series*, ASP, 193