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Authors	FRANCIOSINI, Elena; MAGGIO, Antonio; Pallavicini, R.; REALE, Fabio; TAGLIAFERRI, Gianpiero; et al.
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*Beppo*SAX observations of the rapidly-rotating young star AB Doradus

E. Franciosini, A. Maggio, R. Pallavicini

Osservatorio Astronomico di Palermo, I-90134 Palermo, Italy

F. Reale

Dipartimento di Scienze Fisiche e Astronomiche, Università di Palermo, I-90134 Palermo, Italy

G. Tagliaferri

Osservatorio Astronomico di Brera, I-22055 Merate, Italy

G. Cutispoto

Osservatorio Astrofisico di Catania, I-95125 Catania, Italy

M. Güdel, M. Audard

Paul Scherrer Institute, CH-5332 Villigen, Switzerland

Abstract. The young rapidly-rotating star AB Doradus has been observed by *Beppo*SAX on four occasions in Nov 1998, Dec 1999 and June 2000. In all occasions it was very active with spectacular flares detected up to energies of ~ 50 keV at the peak of the strongest ones. The individual observations were long enough in several cases to investigate possible rotational modulation effects. Simultaneous optical photometry was obtained at the South African Observatory during the Dec 1999 observation. We present an analysis of the quiescent and flaring emission of AB Dor and we discuss the modelling of the quiescent emission and of the flares with the aid of self-consistent loop models.

1. Introduction

AB Doradus is a nearby ($d = 15$ pc) young (age $\sim 20 - 30$ Myr) star of spectral type K0-1 V, with a rotation period of only 12.4 hours, which makes it one of the most rapidly-rotating stars known. Its coronal emission is characterized by high-level variability, on time scales from minutes to weeks, and by the occurrence of frequent flares.

AB Dor has been observed by *Beppo*SAX four times: on Nov 9, 1997, Nov 29, 1997, Dec 8, 1999, and Jun 3, 2000. During the Dec 1999 observation simultaneous optical photometry was obtained at the South African Observatory. In all occasions the star was very active with large flares (Fig. 1) detected up

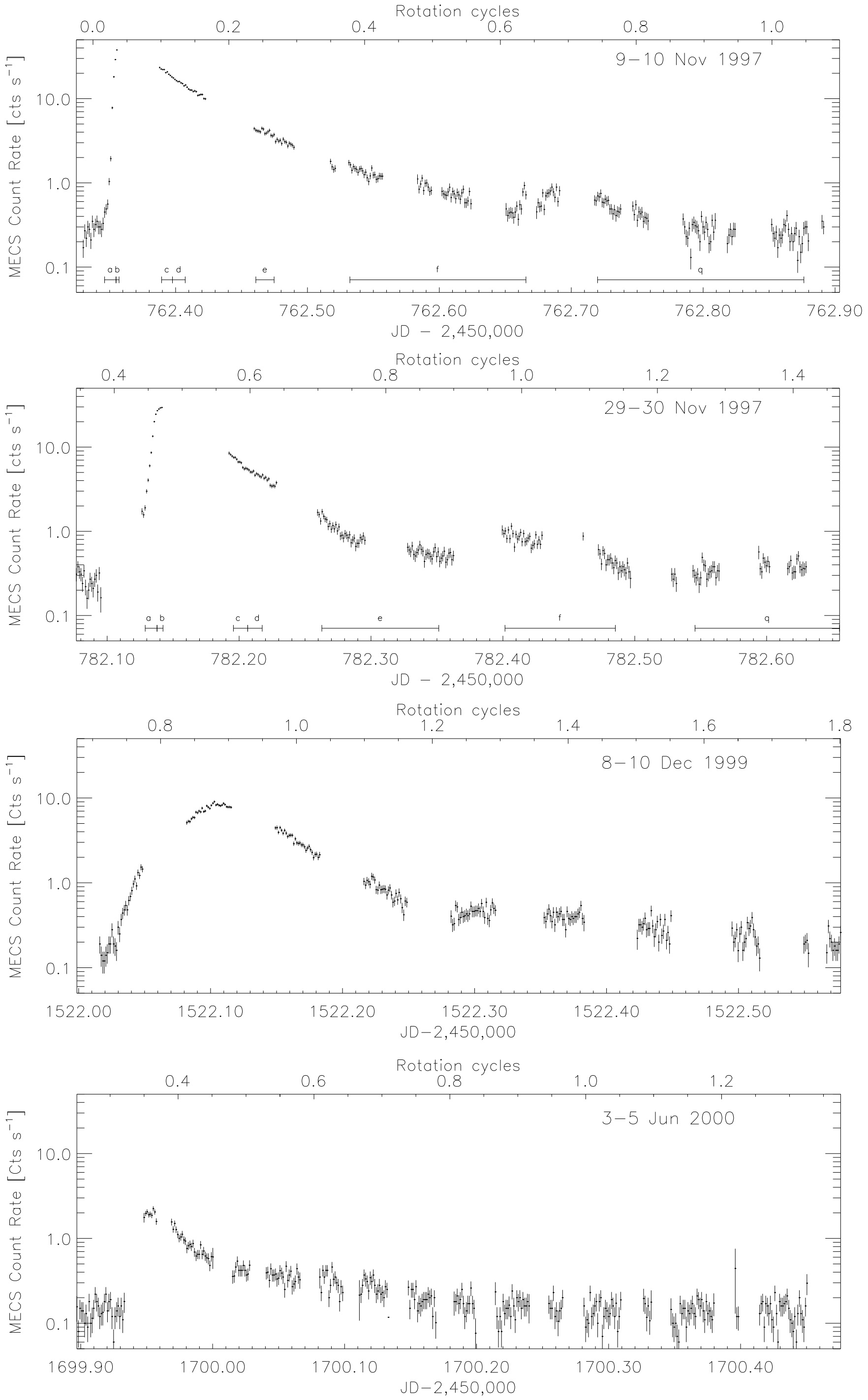

Figure 1. MECS light curves of the four flares observed on AB Dor. Only 50 ksec intervals are shown for each observation. The vertical scale is the same for all observations.

Table 1. Results of the spectral fits during quiescence and during the flares at the times of maximum temperature and/or maximum emission measure. Errors are 68% confidence ranges for three interesting parameters

	$Z/Z_\odot$	$T_1/10^6$ (K)	$T_2/10^6$ (K)	EM_1/EM_2	$EM_2/10^{52}$ (cm^{-3})	χ^2_r	d.o.f.
			Nov 9, 1997				
Quiet	$0.4^{+0.1}_{-0.1}$	$9.3^{+0.8}_{-1.2}$	$29.2^{+4.3}_{-3.0}$	0.55	8.8	0.8	85
Peak T,EM	$0.7^{+0.2}_{-0.2}$		114^{+20}_{-16}		550^{+32}_{-27}	0.8	56
			Nov 29, 1997				
Quiet	$0.6^{+0.1}_{-0.1}$	$8.1^{+0.7}_{-0.3}$	$22.6^{+1.2}_{-0.8}$	0.34	8.2	0.9	90
Peak T	$0.5^{+0.2}_{-0.2}$		100^{+30}_{-19}		366^{+24}_{-24}	1.0	41
Peak EM	$0.6^{+0.2}_{-0.2}$		68^{+10}_{-8}		516^{+32}_{-32}	0.9	49
			Dec 8, 1999				
Quiet pre-fl	$0.2^{+0.1}_{-0.1}$	$9.9^{+0.8}_{-0.7}$	$32.4^{+8.7}_{-5.5}$	2.50	10.4	0.7	116
Quiet post-fl	$0.2^{+0.1}_{-0.1}$	$8.8^{+1.2}_{-1.3}$	$25.2^{+4.2}_{-2.7}$	0.81	7.2	0.8	116
Peak T	$0.3^{+0.2}_{-0.2}$		76^{+16}_{-12}		103^{+8}_{-8}	0.9	58
Peak EM	$0.2^{+0.2}_{-0.2}$		58^{+12}_{-9}		162^{+17}_{-14}	0.8	58
			Jun 3, 2000				
Quiet	$0.3^{+0.2}_{-0.1}$	$8.2^{+1.6}_{-1.8}$	$19.8^{+7.2}_{-27.}$	1.03	4.4	0.8	104
Peak T,EM	$0.7^{+0.5}_{-0.4}$		53^{+18}_{-11}		32^{+5}_{-4}	0.5	58

to energies of ~ 50 keV at the peak of the strongest ones. The Nov 1997 flares started just at the beginning of both observations, while in Dec 1999 and in Jun 2000 the flares occurred in the middle of the observing runs, allowing us to study the quiescent emission both before and after the flare (see Fig. 1 in Pallavicini et al. 2000).

Time-resolved spectroscopy was performed for all observations. For the quiescent emission, LECS and MECS spectra have been fitted simultaneously using a two-temperature MEKAL model with variable global metal abundance. During flares, only MECS spectra have been fitted using a one-temperature variable model plus the fixed quiescent contribution. In Tab. 1 we show the results obtained during quiescence and at the times of maximum temperature and maximum emission measure during the flares.

2. Flare analysis

We have analyzed the decay of the Nov 9, 1997 and the Dec 8, 1999 flares using two different approaches:

1. the method developed by Reale et al. (1997), based on detailed hydrodynamic modeling of magnetically-confined plasma in a single coronal loop

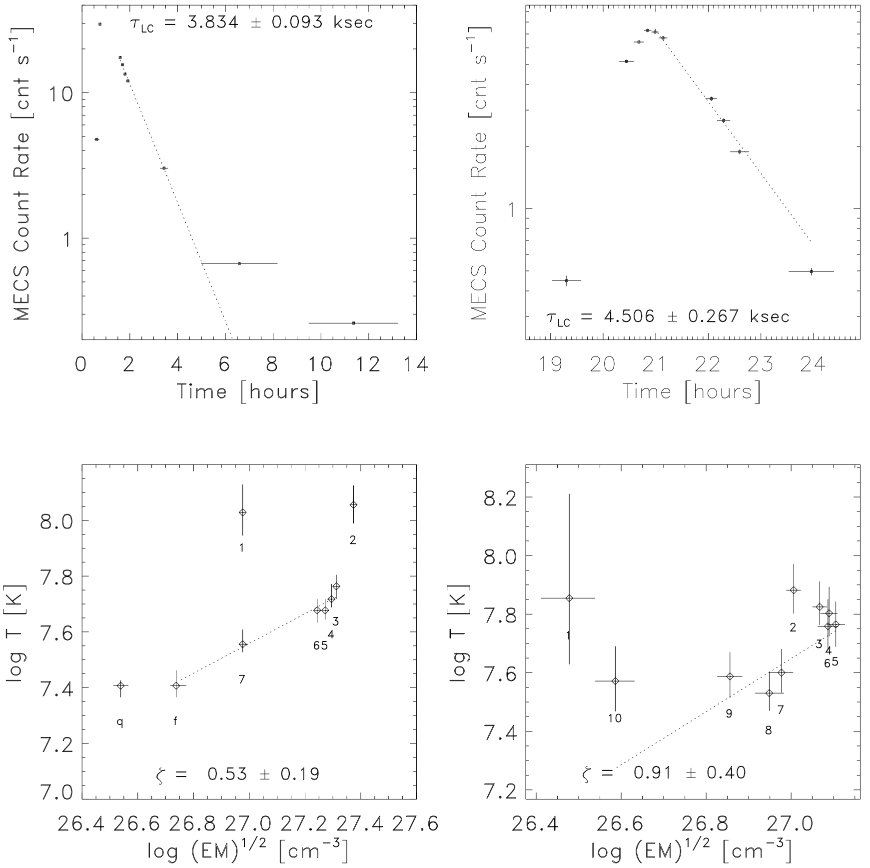

Figure 2. Analysis of the Nov 9, 1997 (*left*) and Dec 8, 1999 (*right*) flares using the Reale et al. (1997) method. The top panels show the MECS light curves and the best-fit exponential decay law; the bottom panels show the flare evolution and best-fit linear regression curve in the $\log T$ vs $\log \sqrt{EM}$ diagram

with fixed geometry, which allows deriving the flaring loop length from the light curve decay time τ_{LC} and from the slope ζ of the linear decay path in the $\log \sqrt{EM} - \log T_{\rm obs}$ diagram. The method has been calibrated for the *Beppo*SAX/MECS response (see Maggio et al. 2000 for details).

2. the two-ribbon flare model developed by Kopp & Poletto (1984) and extended to the stellar case by Poletto et al. (1988), which assumes a growing system of loops formed by reconnection of open field lines at progressively higher altitudes during the flare. This model allows deriving the magnetic field strength in the flaring region for a given loop size.

The first method (Fig. 2) yields a loop size about half the stellar radius for the Nov 1997 flare, while in order to describe the Dec 1999 data a flaring loop with length $\lesssim 1.4\ R_*$ is required. The two-ribbon flare model can describe the data with good accuracy (except for the initial rise phase, which is beyond the

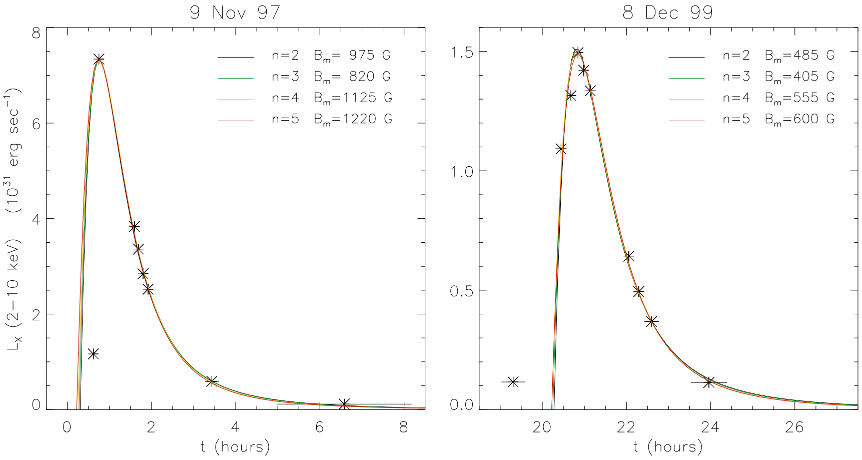

Figure 3. Fit of the flare light curves using the two-ribbon flare model (Kopp & Poletto 1984). n is the order of the Legendre polinomial describing the loop (smaller values of n imply larger loops).

applicability of the model) but the size of the loop cannot be uniquely determined (Fig. 3).

3. Quiescent emission

3.1. Variability analysis

We have analyzed the quiescent emission observed in Dec 1999 before and after the flare in search of possible variability. Two different methods have been used:

1. we have applied the method developed by Collura et al. (1987) which allows establishing the presence and amplitude of non periodic variability on relatively short time scales ($\leq$ 1 hour). The results, shown in Fig. 4, indicate that significant variability was present during the quiescent phases on time scales $\leq 10^3$ sec, with an amplitude of $\sim$ 15% in the $0.1 - 6$ keV band (LECS data) and $\sim$ 20% in the $1.7 - 10$ keV band (MECS data).

2. The X-ray LECS and MECS light curves have been folded with the orbital period, in order to look for any rotational modulation of the coronal emission. The comparison with the optical light curve observed simultaneously at the South African Observatory, shown in Fig. 5, suggests that part of the X-ray emission (associated with the hotter plasma, since the modulation is more evident in the MECS) is indeed rotationally modulated, with higher X-ray emission at the time when the star is less spotted.

3.2. Static loop modeling

The quiescent X-ray spectra collected in Dec 1999 have been fitted also with the detailed static coronal loop models described in Ciaravella et al. (1996) and

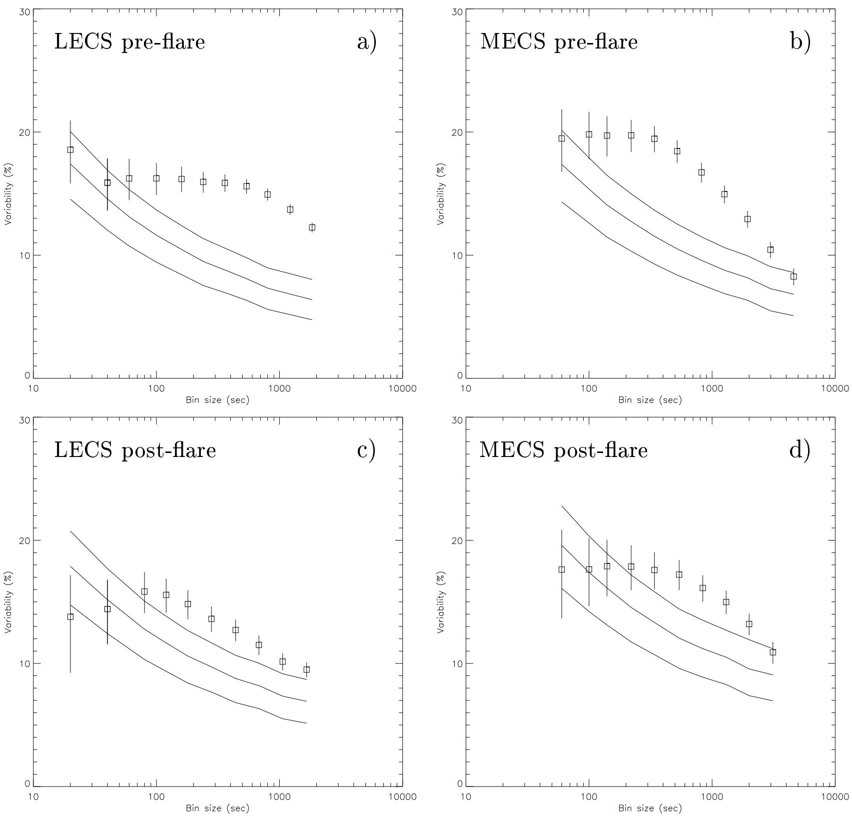

Figure 4. Analysis of the variability of the quiescent emission before and after the flare observed in Dec 1999. The squares with error bars represent the variability level derived from the data using different time bin sizes. Solid lines are the 90%, 95% and 98% statistical confidence levels for detection of variability. The location of the drop in the data points indicates the characteristic time scale of the variability.

Table 2. Results of the fit of the quiescent spectra observed in Dec 1999 using static loop models.

		Cool loop component			Hot loop component		
	$Z/Z_\odot$	$T_{\rm max}$ (10^6 K)	L (cm)	f (%)	$T_{\rm max}$ (10^6 K)	L (cm)	f (%)
Pre-flare	0.35	18	$6\,10^8$	3.0	42	$6\,10^8$	0.1
Post-flare	0.32	18	$6\,10^8$	2.6	38	$6\,10^8$	0.2

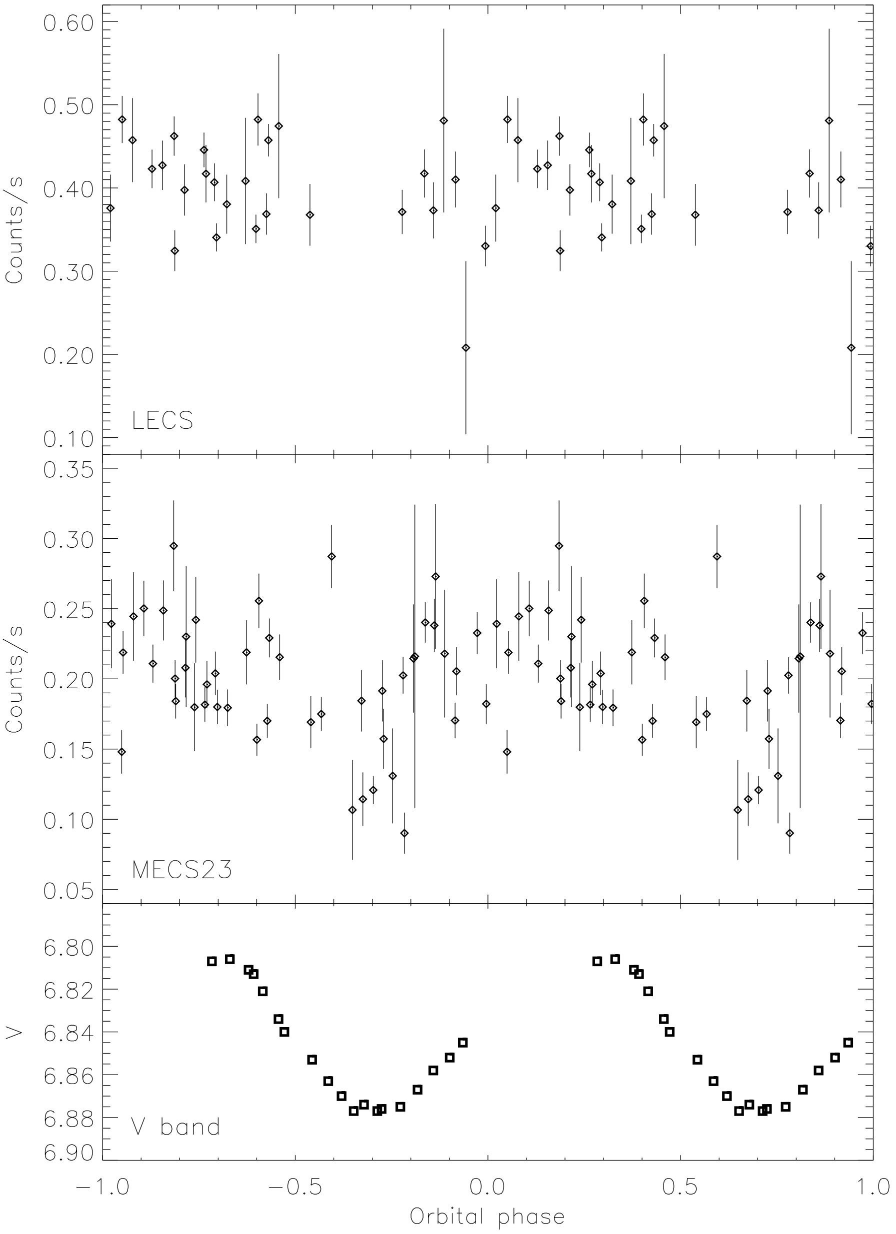

Figure 5. Comparison of the LECS and MECS light curves of the quiescent emission observed in Dec 1999 with the V-band light curve obtained simultaneously at the South African Observatory. The light curves have been folded with the orbital period. Phases have been computed using the ephemeris of Innis et al. (1988)

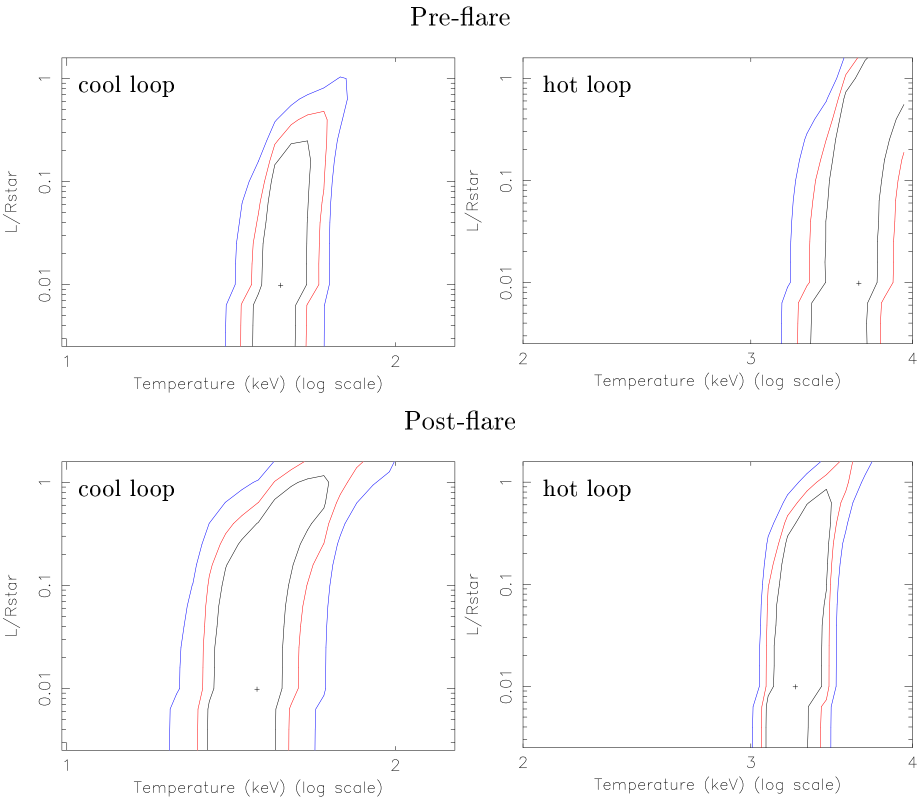

Figure 6. Confidence contours in the plane of the loop model parameters L/R_* (loop semi-length in units of stellar radius) and $T_{\rm max}$ (maximum plasma temperature) for the cool and hot loop components (left and right panels, respectively) required to fit the quiescent X-ray spectra of AB Dor before and after the Dec 1999 flare.

Maggio & Peres (1996). Two loop components are required to fit the data in a satisfactory way. The results (Table 2 and Fig. 6) indicate that the cooler loop component is associated with plasma having maximum temperature $\simeq 20$ MK, confined in loops shorter than the stellar radius, covering a fraction of $\sim 3\%$ assuming $L = 6 \times 10^8$ cm[1]; the hotter loops have instead $T_{\rm max} \simeq 40$ MK and cover a surface fraction 10 times smaller than the cooler loops, assuming the same length, which is not constrained by the modeling. The characteristics of the Dec 1999 flaring loop, derived with the method of Reale et al. (see Sect. 2) are compatible with those allowed by the loop model fitting results, and in

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[1] Note that the loop length and hence the surface filling factor of both loop components are poorly constrained by the fit, as expected for any model loop shorter than the pressure scale height ($H_p \sim 10^{11}$ cm for the cooler loops and $H_p \sim 2 \times 10^{11}$ cm for the hotter loops); in such a case, the fitting quality is almost independent of L, but the surface filling factor scales as $\sim L$.

particular with the pre-flare hot loop component. If such a component is made of loops all of the same length as the flaring one, $L \sim 10^{11}$ cm, the surface filling factor would be $\lesssim 20\%$

4. Conclusions

The large amount of data we have analyzed (see also Maggio et al. 2000) provides us with a quite complex and detailed description of the corona of AB Dor:

- The analysis of the flare decays suggests the presence of flaring loop structures with sizes smaller than (but comparable to) the stellar radius. Continuous heating is usually required during the flare decay phases.
- The variability analysis of the quiescent emission indicates the presence of significant non-periodic variations of the X-ray flux on characteristic time scales $\leq 10^3$ sec, possibly associated with low-level flaring activity. Rotational modulation of the harder component of the coronal emission is also suggested by the comparison with simultaneous optical data.
- The quiescent emission can be described as originating from static coronal loop models, with a cooler component covering a relatively larger fraction of the stellar surface, and a hotter component with smaller surface filling factor (assuming the same loop size). The plasma confined in both classes of coronal loops reaches maximum temperatures > 10 MK at the loop top.

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