X-ray observations of the spotted star AB Dor with *Beppo*SAX

E. FRANCIOSINI[1], R. PALLAVICINI[1], A. MAGGIO[1], G. CUTISPOTO[2], and G. TAGLIAFERRI[3]

[1] INAF – Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, Palermo, Italy
[2] INAF – Osservatorio Astrofisico di Catania, Via S. Sofia 78, Catania, Italy
[3] INAF – Osservatorio Astronomico di Brera, Via E. Bianchi 46, Merate, Italy

Received *July 11, 2002*; accepted *July 11, 2002*

Abstract. The young rapidly-rotating spotted star AB Doradus was observed by *Beppo*SAX on five occasions in November 1998, December 1999, June 2000 and August 2001. In the first four observations 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 induced by starspot associated coronal active regions. Simultaneous optical photometry was obtained at the South African Observatory during the December 1999 observation. We present an analysis of the quiescent and flaring emission of AB Dor and we discuss the implications of these observations for inferring the active region distribution over the star surface. The absence of rotational modulation or of self-eclipses of the longest flares indicate that they are located at high latitudes. The comparison of the X-ray and optical data shows evidence of rotational modulation of the quiescent emission, with higher X-ray emission when the star is less spotted. Intrinsic variations of the coronal emission on time scales of $\sim$ days as well as tens of minutes are also present.

Key words: stars: coronae - stars: activity - stars: late-type - stars: individual (AB Dor) - X-rays

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 five times: on 1997 November 9, 1997 November 29, 1999 December 8, 2000 June 3, and 2001 August 10. During the December 1999 observation simultaneous optical photometry was obtained at the South African Observatory. In the first four occasions the star was very active with large flares (Fig. 1) detected up to energies of $\sim$ 50 keV at the flare peak. The November 1997 flares started just at the beginning of both observations, while in December 1999 and in June 2000 the flares occurred in the middle of the observing runs, allowing us to study the quiescent emission both before and after the flare. During the August 2001 observation, which covered ~ 7.5 rotational periods, the star showed continuous variability at a lower level (Fig. 2).

Spectral analysis with 2-T models shows that the quiescent corona has temperatures of $\sim$ 10 MK and $\sim 20 - 30$ MK and subsolar metal abundances ($Z \sim 0.2 - 0.5 Z_\odot$), with $EM \sim 3 - 8 \times 10^{52}$ cm^{-3}; during the flares temperatures of up to 100 MK are reached.

The X-ray data acquired by *Beppo*SAX on AB Dor are unique. Not only spectacular flares were observed with peak intensities a factor 100 larger than the quiescent emission of the whole star, but the star itself was observed continuously for up to ~ 7.5 rotational periods. This allows us to investigate the temporal behaviour of the high-temperature coronal plasma in AB Dor as well as to infer the spatial distribution of X-ray emitting active regions above the star's surface and its relation to the underlying photospheric spots. In particular, three are the main conclusions that can be derived about the coronal structure of AB Dor from this unique data set: 1) the X-ray emitting coronal active regions are distributed non-uniformely over the stellar surface (as indicated by the presence of rotational modulation) and are predominantly located on the stellar hemisphere opposite to the spotted one (at least during the December 1999 observation, the only one for which we have simultaneous photometric data); 2) in-

Correspondence to: E. Franciosini, francio@astropa.unipa.it

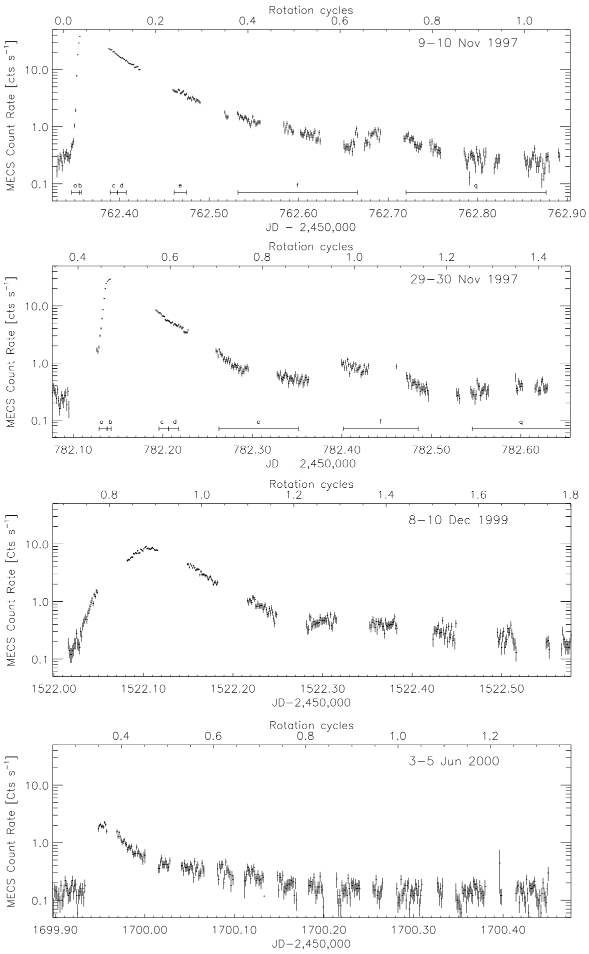

Fig. 1. MECS light curves of the four flares observed on AB Dor in 1997, 1999 and 2000. Only 50 ksec intervals are shown for each observation

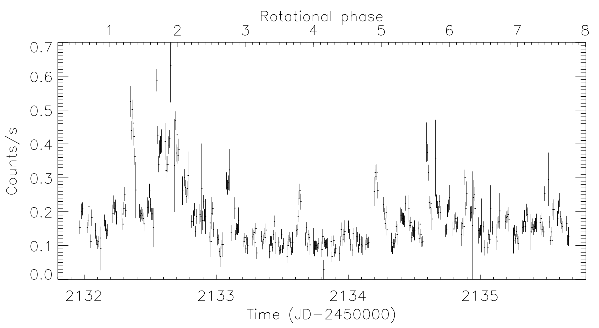

Fig. 2. MECS light curve of AB Dor in August 2001

trinsic variations of the coronal emission not related to the star's rotation occur on times scale of days (~ 2.5 days during the long August 2001 observation) as well as on much shorter time scales ($\leq 10^3$ sec). On the contrary, there was little variation (at most by a factor of 2) of the average quiescent level over ~ 3.5 years; 3) large X-ray flares do occur close to the polar regions indicating that active regions coronal loops must be present at high latitudes in addition to the photospheric spots inferred by Doppler imaging. The observational evidence for these conclusions is briefly presented in the following sections.

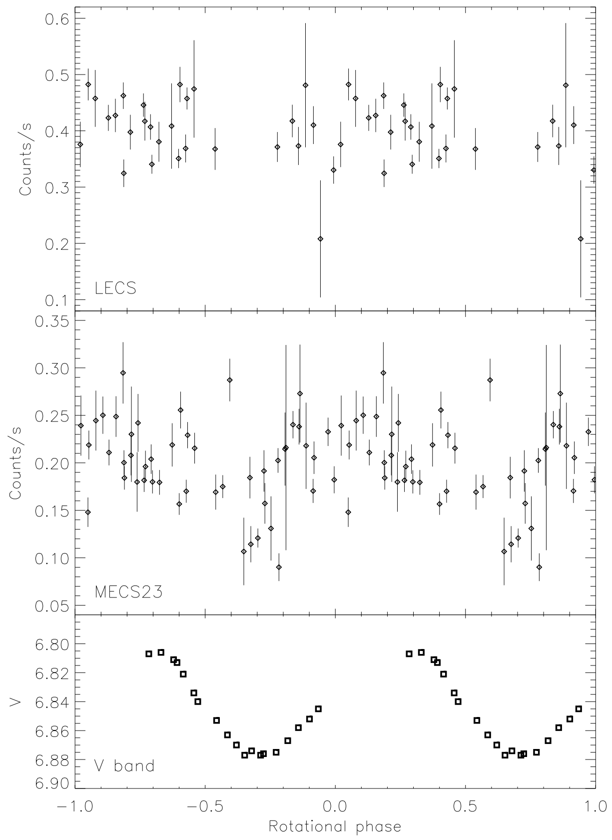

Fig. 3. LECS and MECS light curves of the quiescent emission observed in December 1999, folded with the orbital period, compared with the optical light curve. Phases have been computed using the ephemeris of Innis et al. (1988)

2. Quiescent emission

2.1. Variability analysis

The December 1999 data have been analyzed with the method developed by Collura et al. (1987) which allows to establish the presence and amplitude of non periodic variability on relatively short time scales (≤ 1 hour). The results 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).

2.2. Rotational modulation

The comparison of the December 1999 X-ray light curve, folded with the rotational period, with the simultaneous optical light curve suggests that part of the X-ray emission (associated with the hotter plasma) is indeed rotationally modulated, with the emission peak at the opposite position of the main dark spot (Fig. 3)

The quiescent emission observed in August 2001 shows a long-term modulation (Fig. 4, top panel) over ~ 5 rotational periods (i.e. 2.5 days). Some rotational modulation is also present, as shown in the bottom panels of Fig. 4, where

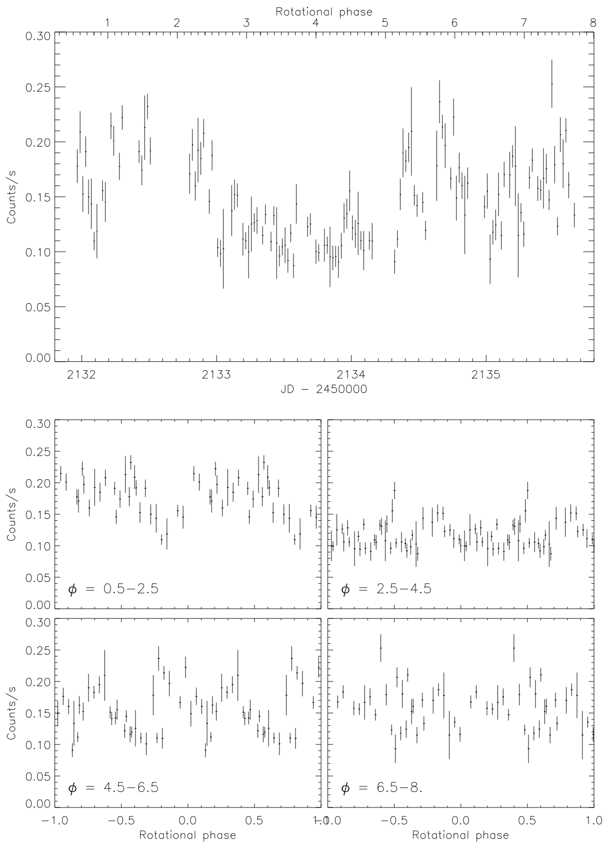

Fig. 4. *Top panel*: MECS quiescent light curve observed in August 2001 (all obvious peaks have been removed). *Bottom panels*: MECS folded light curve divided into four equal intervals lasting 2 rotational periods

the folded light curve has been divided into intervals lasting 2 rotational periods.

2.3. Static loop modeling

The quiescent X-ray spectra collected in December 1999 have been fitted with detailed static coronal loop models, as described in Maggio & Peres (1996). Two loop components are required to fit the data in a satisfactory way. The results (Table 1) indicate that the cooler loop component is associated to plasma with a maximum temperature $\simeq 20$ MK confined in loops shorter than the stellar radius, covering several percents of the stellar surface; the hotter loops have instead $T_{\max} \simeq 40$ MK and cover a surface fraction 10 times smaller than for the cooler loops, assuming the same length (not constrained by the modeling).

3. Flare analysis

We have analyzed the 1997 November 9 and the 1999 December 8 flare decays using two different approaches. We first applied the method developed by Reale et al. (1997), based on detailed hydrodynamic modeling of magnetically-confined plasma in a single coronal loop with fixed geometry, which allows us to derive the flaring loop length from the light curve decay time τ_{LC} and from the slope ζ of the linear

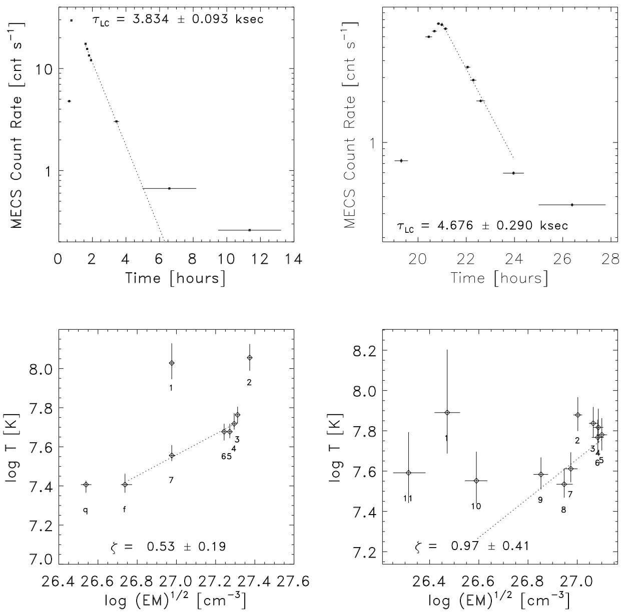

Fig. 5. Flare analysis using the Reale et al. (1997) method for the 1997 November 9 flare (*left panels*) and for the 1999 December 8 flare (*right panels*)

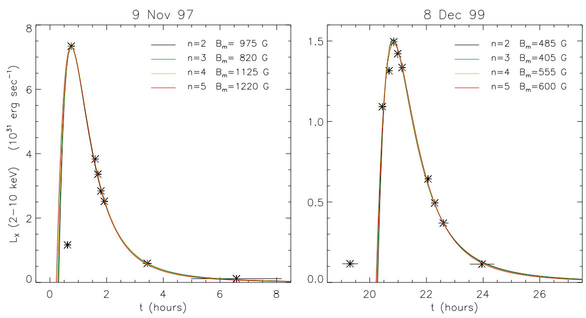

Fig. 6. Fit of the flare light curves using the two-ribbon flare model (Kopp & Poletto 1984). n is the order of the Legendre polinomial describing the loop (smaller n imply larger loops)

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). This analysis (Fig. 5) yields a loop size about half the stellar radius for the November 1997 flare, while in order to describe the December 1999 data a flaring loop with length $\sim 2R_*$ is required.

We also analysed the data using the two-ribbon flare model developed by Kopp & Poletto (1984) as 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 us to derive the magnetic field strength in the flaring region for a given loop size. The two-ribbon flare model can describe the data with good accuracy (except for the initial rise phase, which is beyond the applicability of the model) but the size of the loop cannot be uniquely determined (Fig. 6). If the constraint on the loop length derived with the Reale et al. method is used, the two-ribbon flare modeling suggests that the maximum strength of the magnetic field for

Table 1. Results of the static loop modeling of the quiescent emission in December 1999

		Cool loop component			Hot loop component		
	$Z/Z_\odot$	$T_{\max}$ (10^6 K)	L (cm)	f (%)	$T_{\max}$ (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

the November 1997 flare is $2-3$ times larger than for the December 1999 flare.

4. Conclusions

The large amount of data we have analyzed provides us with a quite complex and detailed description of the corona of AB Dor.

The variability analysis of the quiescent emission confirms 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 long-term monitoring performed in August 2001 over ~ 7.5 rotational periods has evidenced a long-term modulation of the quiescent emission, with a period of $\sim 5P_{\rm rot}$.

The comparison of the five observations shows that the mean level of the quiescent emission changed at most by a factor of 2 over a time span of ~ 3.5 years.

The quiescent emission can be described as originating from static coronal loop models, with a cooler component covering a relatively large fraction of the stellar surface, and a hotter component with smaller surface filling factor (assuming the same loop size). The plasma confined in the two classes of coronal loops reaches maximum temperatures at the loop top of ~ 20 MK and ~ 40 MK, respectively.

The analysis of the flare decays suggests in most cases the presence of flaring loop structures with sizes smaller than the stellar radius, with the notable exception of the loop associated with the December 1999 flare, whose semi-length was $\sim 2R_*$. Continuous heating is usually required during the flare decay phases, except in the last case.

The absence of modulation or self-eclipses during the longest flares suggests that they occurred in regions close to the stellar poles, in agreement with the location of magnetic structures inferred from optical observations.

References

Collura, A., Maggio, A., Sciortino, S., Serio, S., Vaiana, G. S., Rosner, R.: 1987, ApJ 315, 340

Kopp, R.A., Poletto, G.: 1984, Solar Phys. 93, 351

Innis, J.L., Thompson, K., Coates, D.W., Evans, T.L.: 1988, MNRAS 235, 1411

Maggio, A., Pallavicini, R., Reale, F., Tagliaferri, G.: 2000, A&A 356, 627

Maggio, A., & Peres, G.: 1996, A&A 306, 563

Reale, F., Betta, R., Peres, G., Serio, S., McTiernan, J.: 1997, A&A 325, 782

Poletto, G., Pallavicini, R., Kopp, R. A.: 1988, A&A 201, 93