X-ray observations of stellar coronae and flares with BeppoSAX

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Abstract. In the four years since its launch the Italian/Dutch satellite *Beppo*SAX has obtained many new interesting results on X-ray emission from stellar coronae and transient events. These results include the determination of the temperature structure of stellar coronae, the detection for the first time of hard (> 20 keV) X-ray emission tails, the determination of coronal abundances and the time evolution of coronal parameters (including metallicity) in the course of flares. We show several examples of the acquired data with emphasis on observations by our team of the RS CVn binaries UX Ari, HR 1099 and II Peg, of the flare star YY Gem and of the young ZAMS star AB Dor. We present the observational results and the modeling carried out for their interpretation.

1. Introduction

Of the X-ray satellites now in orbit, or to be launched in the near future, the Italian-Dutch satellite *Beppo*SAX is the only one capable of observing sources simultaneously over more than three decades of energy, from 0.1 keV to more than 200 keV. This broad-band capability makes *Beppo*SAX observations unique and scientifically valuable even now that much more powerful X-ray missions (Chandra and XMM-Newton) are in orbit. This broad-band capability is important for all types of X-ray sources and even for relatively soft sources, like stellar coronae. This is illustrated by Fig. 2 which shows the broad-band spectrum of a large flare from the nearby star AB Dor observed by all instruments onboard *Beppo*SAX: the Low Energy Concentrator Spectrometer LECS (0.1-10 keV), the Medium Energy Concentrator Spectrometers MECS ($1-10$ keV), the High Pressure Gas Scintillation Proportional Counter HPGSPC ($3-120$ keV) and the Phoswich Detector System PDS ($15-300$ keV).

With specific regard to stellar coronae, the *Beppo*SAX mission, in addition to detecting for the first time hard (> 20 keV) X-ray emission from stellar sources other than the Sun, has allowed studying the temperature structure of coronae, their chemical composition and their time-variability, including the monitoring of rotational modulation and eclipses and the detection of a number of spectacular

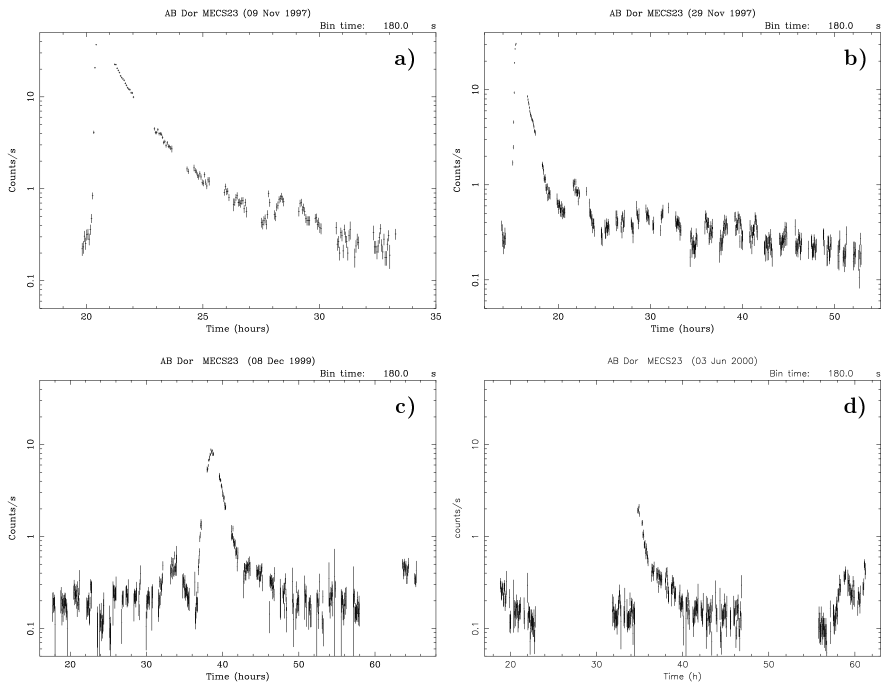

Figure 1. MECS light curves of AB Dor observed on Nov 9, 1997 (a), Nov 29, 1997 (b), on Dec 8, 1999 (c) and June 3, 2000 (d). The vertical scale is the same for all panels.

flares. In this paper, we present examples of the acquired data, with emphasis on observations obtained by our teams at the Osservatorio Astronomico di Palermo and Osservatorio Astronomico di Brera.

2. The young rapidly-rotating star AB Dor

AB Doradus (HD 36705) is a nearby young ($20-30$ Myr) rapidly-rotating K0-1V star with a rotation period of 12.4 hours. It has been observed by *Beppo*SAX four times, twice in Nov 1997 (on the 9th and 29th; see Maggio et al. 2000) and again in Dec 1999 and June 2000 (Franciosini et al. 2000b). All observations showed spectacular flares (Fig. 1), with peak temperatures up to $> 10^8$ K and clear detection of hard (> 20 keV) X-ray emission by the PDS instrument. The coronal metallicity is always strongly subsolar ($\sim 0.2 - 0.3$ solar), in spite of the measured solar photospheric abundance of this star, with some indication that the coronal metallicity may have increased by up to a factor of 3 at the flare peak, as observed in other large flares seen with *Beppo*SAX (e.g. Algol, Favata & Schmitt 1999) and ASCA (e.g. UX Ari, Güdel et al. 1999). A detailed discussion of our *Beppo*SAX observations of AB Dor, and of the modelling of the flares with the confined-loop hydrodynamic-decay approach of Reale et al. (1997) is presented in Maggio et al. (2000) and Franciosini et al. (2000b). Here we concentrate only on the detection of hard X-ray emission by the PDS instrument in the Nov 1997 flares.

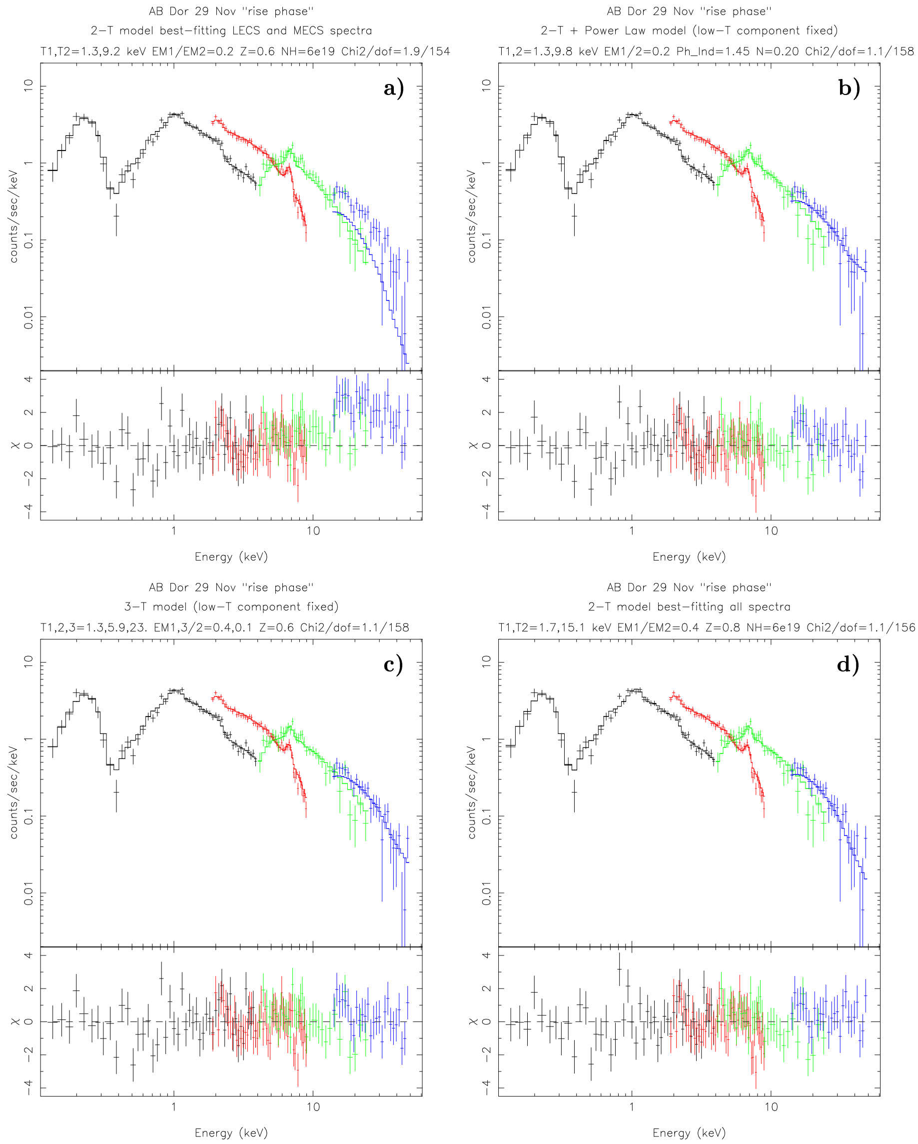

Figure 2. Broad-band spectrum of AB Dor observed during the rise phase of the Nov 29, 1997 flare by all *Beppo*SAX instruments (LECS, MECS, HPGSPC and PDS). The figure shows the fit obtained **a)** by extrapolating the 2-T model that best fits the LECS+MECS data alone; **b)** by adding to the 2-T model a power-law component; **c)** by adding to the 2-T model a third thermal component at higher temperature; **d)** by fitting the whole spectrum with a 2-T model

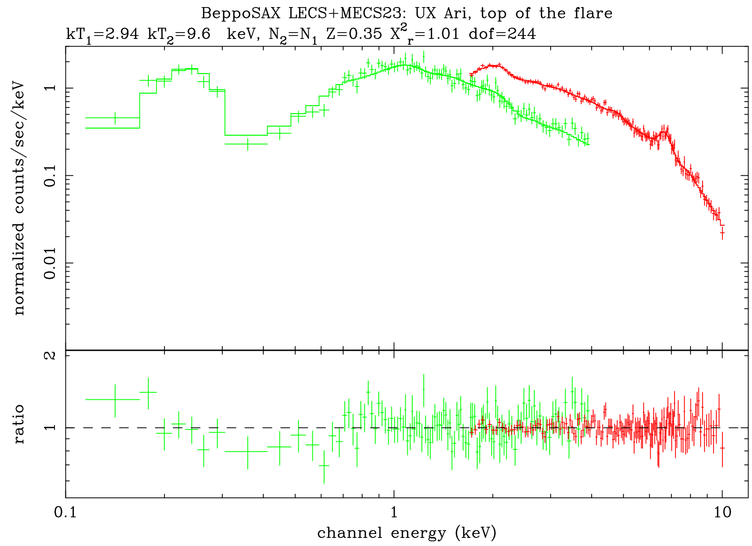

Figure 3. Best-fit of the LECS+MECS spectrum of UX Ari at the peak of the flare observed in August 1997

The basic question one would like to answer in this respect is whether the observed hard X-ray emission is thermal, and due to the very-high temperatures reached at the flare peak, or non-thermal, i.e. due to a stream of accelerated electrons similar to those observed in the impulsive phase of solar flares. Fig. 2a shows, for the Nov 29, 1997 flare, the result of extrapolating to higher energies the 2-temperature (2-T) thermal model that best fits the LECS and MECS data alone. An excess emission at higher energies is clearly seen. This excess emission seen by the PDS can be fitted by adding either a non-thermal power-law component (Fig. 2b) or a third thermal component at higher-temperature (Fig. 2c). The LECS, MECS and PDS data can also be fitted simultaneously with a 2-T thermal model with temperatures somewhat higher than those fitting the LECS and MECS data alone (Fig. 2d). From this we conclude that there is no need to invoke the existence of a non-thermal population of accelerated electrons and that the hard-X-ray tail seen by the PDS can simply be explained by the extremely high-temperatures ($> 10^8$ K) reached in the rise phase and at the peak of large stellar flares.

3. The RS CVn binary UX Ari

UX Arietis is one of the most active RS CVn binary systems, consisting of a G5V and a K0IV star, with an orbital period of 6.44 days. The source has been observed twice by *Beppo*SAX, in Aug 1997 and Aug 1998. During the first observation, a large long-duration flare was observed from shortly before the peak to the late decay. Time-resolved spectroscopy during the flare shows that temperatures of the order of 10^8 K were reached at the flare peak (Fig. 3) and these very high temperatures were mainly responsible for the hard (> 20 keV)

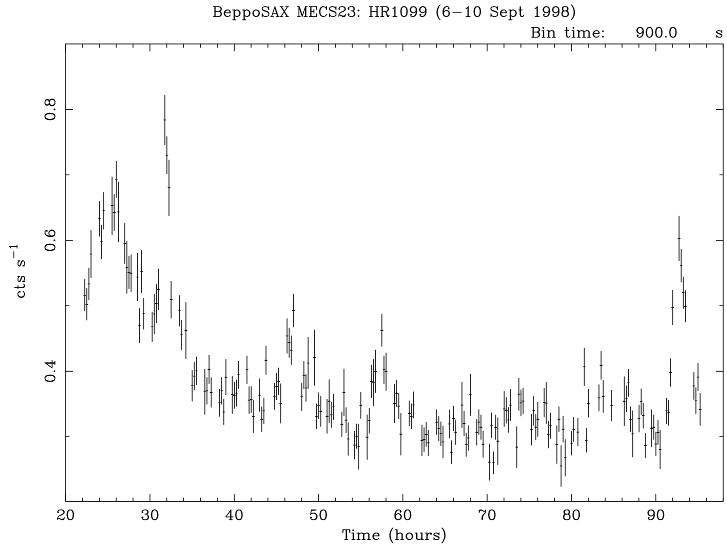

Figure 4. MECS light curve of HR 1099 observed in September 1998

X-ray excess observed at the same time by the PDS. In the second observation performed in Aug 1998 simultaneously with radio observations at the VLA, UX Ari was quiescent for the entire observation (59 hours) at a level only a factor 2 lower than observed at the very end of the Aug 1997 flare (Franciosini et al. 2000a). The coronal metallicity in both cases resulted to be strongly subsolar ($\sim 0.2 - 0.3$ solar) in agreement with previous results by ASCA. Modelling the Aug 1997 flare with the 2-ribbon reconnection model of Kopp & Poletto (1984) results in an acceptable fit (Franciosini et al. 2000, in preparation).

4. The RS CVn binary HR 1099

HR 1099 (V711 Tauri) is one of the brightest RS CVn binaries, formed by a G5IV and a K1IV star, orbiting each other with a period of 2.84 days. The source was observed by *Beppo*SAX in September 1998 for a full orbital period, as part of a multi-wavelength campaign including also EUVE observations and radio observations at the Australia Telescope, the VLA and the European VLBI Network (Osten et al. 2000, in preparation; Trigilio et al. 2000). Fig. 4 shows the MECS light curve: significant variability is present, but no major flare was detected. Moreover, there was poor correlation (if any) between radio and X-ray variability, as in the Aug 1998 observation of UX Ari (Franciosini et al. 2000a). Spectral fits with 2-T models give temperatures and coronal metallicities rather similar to those obtained for UX Ari in quiescence. As for UX Ari, and typically for all coronal sources observed with *Beppo*SAX, the hydrogen column density necessary to fit the data is significantly higher (by one order of magnitude or more) than expected from the distance and celestial position of the source. Although intrinsic absorption at the source has been occasionally postulated (e.g. for the eclipsing RS CVn binary AR Lac observed with *Beppo*SAX by Rodonò et al. 1999), this explanation cannot hold for HR 1099, because a large

N_H would be inconsistent with the observed EUV lines. Errors in the LECS low energy calibration are a more likely explanation. New response matrices released recently have significantly alleviated (but not completely eliminated) the problem, as shown by a reanalysis of some *Beppo*SAX stellar observations with the new and old matrices.

5. The RS CVn binary II Peg

II Pegasi (HD 224085) is a single-line RS CVn binary composed of a K2-3 IV-V primary and an unseen secondary, with an orbital period of 6.7 days. It was observed twice by *Beppo*SAX, in Dec 1997 and June 1999. During the first observation, the late decay of what seems a long-duration flare was observed, but nothing could be said about the actual duration of the flare and the peak time. A 2-T model indicates temperatures in the range $9-11$ and $24-26$ MK, respectively. The derived metallicity (~ 0.2 solar) is significantly lower than recent determinations of the photospheric abundance of the star (~ 0.6 solar; see Covino et al. 2000). As for other stellar sources observed by *Beppo*SAX, the derived hydrogen column density N_H is about a factor 10 higher than previously determined.

6. The eclipsing binaries HD 9770 and YY Gem

HD 9770 is a visual triple system containing a recently discovered (Cutispoto et al. 1997) short-period (~ 0.48 days) eclipsing binary of the BY Dra type, formed by two nearly identical stars of spectral type K5V. This system was observed by *Beppo*SAX on Dec 1996 for 3.7 orbital cycles, revealing significant modulation of the quiescent emission due to rotation and eclipses as well as intrinsic variability due to the occurrence of moderate-size flares (Tagliaferri et al. 1999). Spectral fits of the LECS and MECS data with 2-T models indicate low coronal abundances (~ 0.3 solar) consistently with what typically found by both *Beppo*SAX and ASCA for active stars. Unfortunately, the photospheric metallicity of this star in not known and thus it cannot be established whether the coronal and photospheric metallicities are indeed different.

YY Geminorum (Castor C) is another well-known eclipsing binary system of the BY Dra type, formed by two dM1e stars, orbiting each other with a period of 0.81 days. It is part of the sextuple system Castor ABC, each of the three visual components being itself a spectroscopic binary. Castor C (YY Gem) is 73 arcsec from Castor AB, which is itself an X-ray source, previously detected by EXOSAT and ROSAT, and now also by XMM-Newton (Güdel et al. 2000). The proximity of the two sources makes it difficult to separate YY Gem and Castor AB with *Beppo*SAX: yet a preliminary analysis of the data (Fig. 5) indicates that the strong erratic variability and flare activity observed from this system by *Beppo*SAX over 5.9 orbital cycles seems modulated with the YY Gem orbital period and most likely originated from YY Gem itself (Tagliaferri et al. 2000). Spectral analysis indicates a 2-temperature corona with subsolar metal abundance. The latter increased by more than a factor of 3 during a large flare.

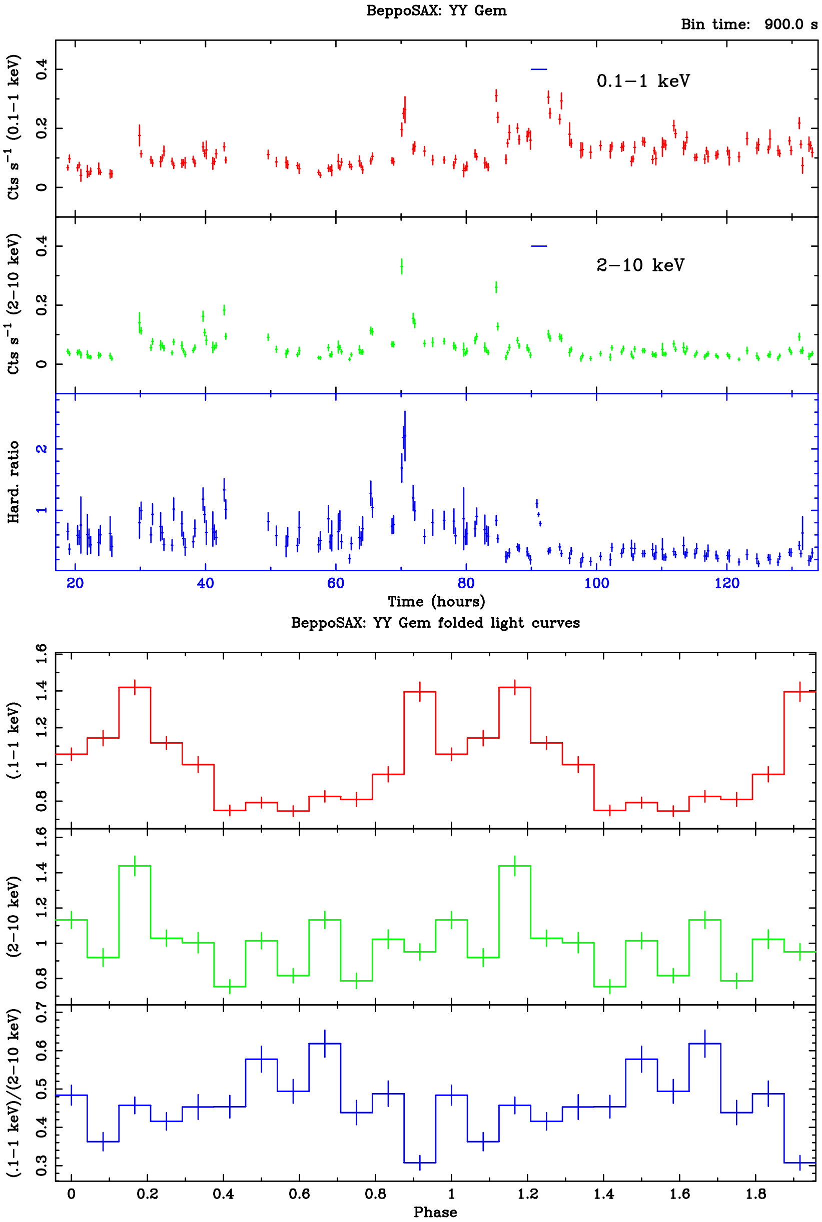

Figure 5. LECS (0.1-1 keV) and MECS (2-10 keV) light curves of YY Gem and their hardness ratio as a function of time (*upper panel*) and folded with the YY Gem orbital period (*lower panel*)

7. Conclusions

We have presented several examples of stellar coronal observations carried out with *Beppo*SAX as part of Guest Observer programmes by our two collaborating teams. These data, together with those obtained by other guest observers, allow us to draw the following conclusions:

- The coronae of active stars are best described, at the *Beppo*SAX spectral resolution, by 2-T models with typical temperatures of, respectively, $6-10$ MK and $20-25$ MK.
- Higher temperatures occur during flares and extremely high temperatures ($> 10^8$ K) are reached at the peak of large flares.
- The coronal metallicity of active stars is usually much lower than solar and, at least in some cases, is also lower than the photospheric metallicity of the same stars. There are indications that the coronal metallicity increases during flares, typically by factors of 3.
- The hydrogen colum density necessary to fit *Beppo*SAX data is systematically much larger than expected, most likely because of calibration problems of the LECS detector at low energies.
- Strong erratic variability is typically present in coronal sources, both at low level and in the form of exceptionally large flares. Evidence has been found in some cases for rotational modulation and eclipses.
- Hard (> 20 keV) X-ray emission has been detected in the rise phase and at the peak of large flares. This emission is most likely of thermal origin.
- Solar-type loop models have been successfully used to model *Beppo*SAX stellar observations, under both quiescent and flaring conditions, thus providing insights into the geometry and size of coronal structures.

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