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BeppoSAX observations of Polars

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Abstract. We present the first *BeppoSAX* Narrow Field Instrument observations obtained within a program aimed at detecting the soft and hard X-ray emissions of polars simultaneously, and of studying their long term behaviour. BL Hyi, AM Her and the peculiar V1309 Ori show examples of the different accretion patterns and modes which can be present in these systems.

1 Introduction

With the launch of the *BeppoSAX* satellite in April 1996, the opportunity to gather simultaneous X-ray observations of the wide energy range 0.1–300 keV has raised great interest in many astrophysical fields. In particular, for magnetic cataclysmic variables (mCVs) this type of observations is crucial in determining the different components which characterize their X-ray emission and to provide constraints on the accretion parameters and energy budgets. For polars, these observations are even more important, given the long term variability in both luminosity level and light curve shapes. More specifically, the study of light curves in the soft and hard X-ray bands and the determination of the relative proportion of the soft and hard X-ray luminosities are fundamental for our understanding of the actual accretion mode and irradiation processes. Also, long term luminosity variations are indicative of changes in the mass transfer rate from the secondary star, whose origin is still poorly understood.

The *BeppoSAX* satellite carries four co-aligned Narrow Field Instruments (NFIs) as prime pointing instruments (see Boella et al. 1997 and references therein for a detailed description). They consist of a Low Energy Concentrator Spectrometer (LECS) covering the soft X-ray band from 0.1 to 10 keV with an effective area 20 cm^2 at 0.25 keV, and three units of the Medium Concentrator Spectrometer (MECS) covering the range 1.3–10 keV, one unit of which ceased operating in May 1997, giving a current effective area of 96 cm^2 at 6 keV. Both

LECS and MECS have an energy resolution of 8% at 6 keV. Due to sunlight contamination, the LECS can be operated only in earth shadow, thus its efficiency is typically 30%–60% of that of the MECS. The two higher energy instruments are the High Pressure Gas Scintillation Proportional Counter (HPGSPC) covering the 3–120 keV range with a geometrical area of 450 cm^2 and energy resolution of 4% at 60 keV, and the Phoswich Detector System (PDS) covering the range 15–300 keV with an area of 800 cm^2 and an energy resolution of 16% at 60 keV. The satellite also carries two Wide Field Cameras, mounted perpendicularly to the NFIs, each covering the 2–30 keV range with a $20^\circ \times 20^\circ$ field of view.

Here we present the first NFIs observation of the three polars, BL Hyi, AM Her and V1309 Ori, acquired during the AO-1 observing cycle in the context of a Core Program aiming to detect the soft and hard X-ray emission simultaneously and to study the long term behaviour of magnetic CVs.

2 The variability of BL Hyi

BL Hyi is known to display high and low states on timescales of years, with a pronounced flaring activity at increased luminosities (Beuermann & Schwope 1989; Schwope 1993; Ramsay et al. 1996). This activity was found to be soft (20–27 eV), with the source occasionally switching off during orbital minima.

BL Hyi was observed on 1996 September 27 and detected by the MECS (three units) and the LECS only, at average count rates of $0.12\,s^{-1}$ and $0.02\,s^{-1}$ respectively. The effective exposure time was 12.5 ksec for the MECS and, due to its operational limitation, 3.7 ksec for the LECS. BL Hyi was at an intermediate state, being 1.2 times fainter than when observed in 1994 by *ASCA* and twice as bright as in the intermediate state observed by *EXOSAT* in 1985.

The short duration of the LECS observation prevents any variability study, while the MECS light curve, presented in Fig. 1, clearly shows the 114-min orbital periodicity with strong cycle-to-cycle variations during the faint phase, which are thus related to the secondary pole activity, which almost switches off during the second observed cycle. These observations indicate that the secondary pole is indeed active in the hard X-rays, as found in the *ASCA* data. However, the uneven coverage of the faint phase of the *ASCA* data hampers information on the variability of the secondary pole. This is clearly found in this *BeppoSAX* observation, which indicates an unsteady accretion onto the secondary pole. On the other hand, the X-ray-bright phase related to the main pole does not change its morphology with respect to previous observations.

The mean MECS spectrum allows a precise temperature determination using a simple Raymond-Smith model $kT_{\rm RS} = 9.8^{+3.0}_{-1.9}$ keV setting $A_{\rm Z}$ to solar values, thus giving a bolometric flux of $1.4 \times 10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}$. This temperature is confirmed also by the *ASCA* data, given the inclusion of partial cold absorption or of a cold reflection component and of a 6.4-keV iron fluorescent line (see Matt et al. 1998 for a detailed discussion of the *ASCA* and *BeppoSAX* spectra). Moreover, the combined MECS+LECS fit gives zero blackbody flux, the 90% upper limit to this component implying a bolometric flux less than 10 times that of the hard one. This indicates that at intermediate levels no soft excess is present.

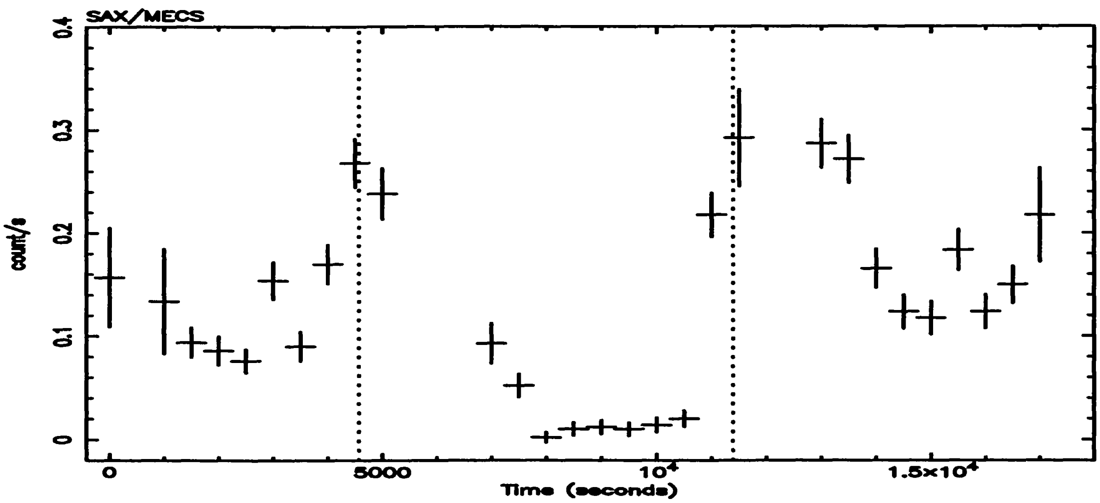

Figure 1. The MECS light curve of BL Hyi in September 1996 showing strong cycle-to-cycle variability related to the secondary pole. Vertical dotted lines indicate orbital phase zero.

3 The peculiar variability of V1309 Ori

The recently discovered eclipsing system V1309 Ori (RX J0515.6+0105) is the longest period (7.98 hr) polar (Garnavich et al. 1994; Shafter et al. 1995). It possesses soft X-ray emission which is extremely variable on timescales of few seconds and interpreted as the evidence of "blobby" accretion (Walter et al. 1995). No constraints on the hard-X-ray component could be established from the *ROSAT* data alone. V1309 Ori was also found to be variable on a long-term timescale while keeping its flaring behaviour.

V1309 Ori was observed on 1996 October 5 and detected by the LECS and the MECS (three units) at average count rates of $7.4 \times 10^{-3}\,s^{-1}$ and $2.7 \times 10^{-3}\,s^{-1}$ and with total effective exposure times of 10 ksec and 60 ksec respectively. V1309 Ori was at comparable level to that observed by *ROSAT* in 1991 and it was roughly half as bright as when observed in 1992/1993.

The LECS hardness ratio [(2–10 keV)–(0.1–2 keV)]/[(0.1–2 keV)+(2–10 keV)] = –0.22 indicates a dominant soft-X-ray component and hence the LECS and MECS light curves, shown in Fig. 2, indicate the behaviour of the soft and hard components respectively. Both show a marked bursting activity consisting of discrete events on timescales $\lesssim$ 30 min. The bursts do not always coincide in the two detectors. The source is also observed to switch off occasionally. Furthermore, no bursting periodicity at the orbital period is detected, in contrast to results with *ROSAT*. The partial coverage of the eclipse phases, and the low intensity of the source, hamper any search for X-ray eclipses (see also Szkody et al., this volume).

The combined LECS and MECS spectrum is fitted with two components: a blackbody at $kT_{BB} = 30^{+30}_{-21}$ eV and a Raymond-Smith at $kT_{RS} = 10^{+\infty}_{-5}$ keV with fixed $A_Z = 1$. $N_H = 4 \times 10^{20}\,cm^{-2}$ was unconstrained, but compatible with *ROSAT* results (see de Martino et al. 1998a for a detailed discussion). For a 10-keV hard component and a 30–50-eV blackbody and $N_H = 4–5.4 \times 10^{20}\,cm^{-2}$

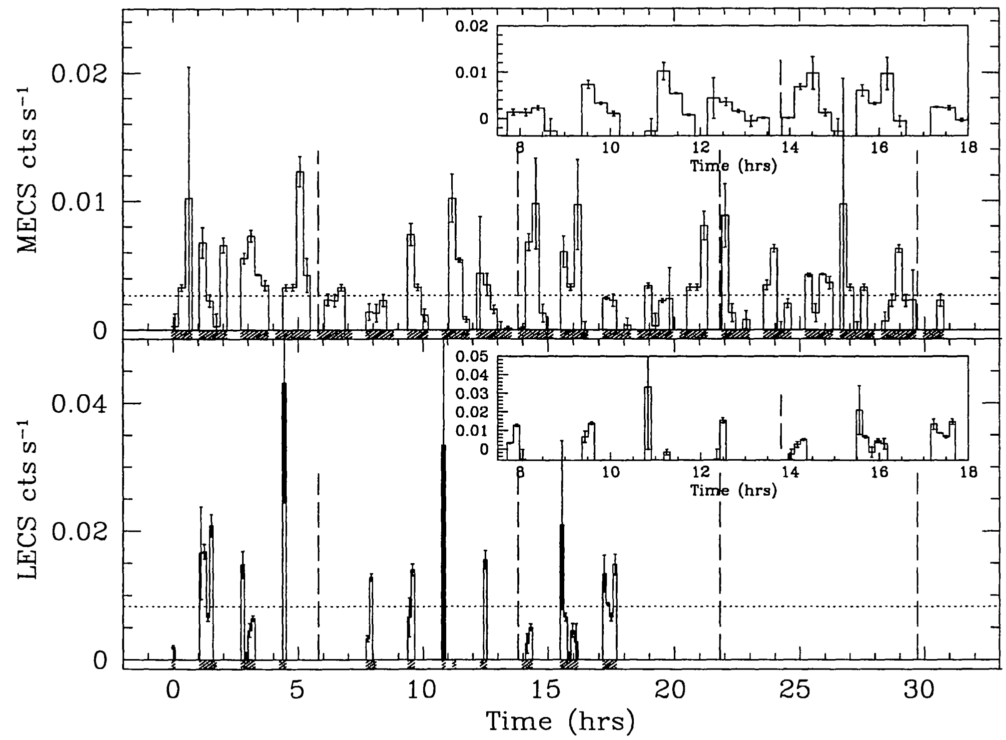

Figure 2. The net light curves of V1309 Ori in the LECS (lower panel) and the MECS (upper panel) averaged in 500-s and 1000-s bins respectively. The mean count rates are shown with a horizontal line. The effective on-source windows are marked as shaded areas. Inserted panels show the switching off of the X-ray flux. Vertical dashed lines represent the eclipse times.

an extreme luminosity ratio $L_{soft}/L_{hard} \sim 64$–160 is found. Furthermore for a distance of 650 pc (de Martino et al. 1998a) a covering factor $f = 7 \times 10^{-5}$ is found for the soft emitting region. An accretion rate $\dot{M} = 1.6\text{–}4 \times 10^{16}\,\mathrm{g\,s^{-1}}$ and a local mass accretion rate $\dot{m} = 16\text{–}35\,\mathrm{g\,cm^{-2}\,s^{-1}}$ are derived.

The derived high luminosity ratio appears consistent with a high local $\dot{m}$ regime (Beuermann 1998) which favours a non-standard blobby-accretion mode. The highly variable hard X-ray emission can then be accounted for by this accretion mode, which makes V1309 Ori a test case for further detailed theoretical work.

4 The long term variability of AM Her

AM Her was observed on 1997 September 6, during one of its deepest and most prolonged ($\sim$ 9 months) low states at $V = 15.1$ mag, and on 1998 May 8, when it was at $V = 14.3$ mag, just after a brightening occurred in April.

4.1 An activity event during a deep low state

In September 1997, AM Her was detected by the LECS and the MECS (two units) at average count rates of $7 \times 10^{-3}\,s^{-1}$ and $0.012\,s^{-1}$ respectively for a total exposure time of 9.8 ksec and 24.7 ksec respectively.

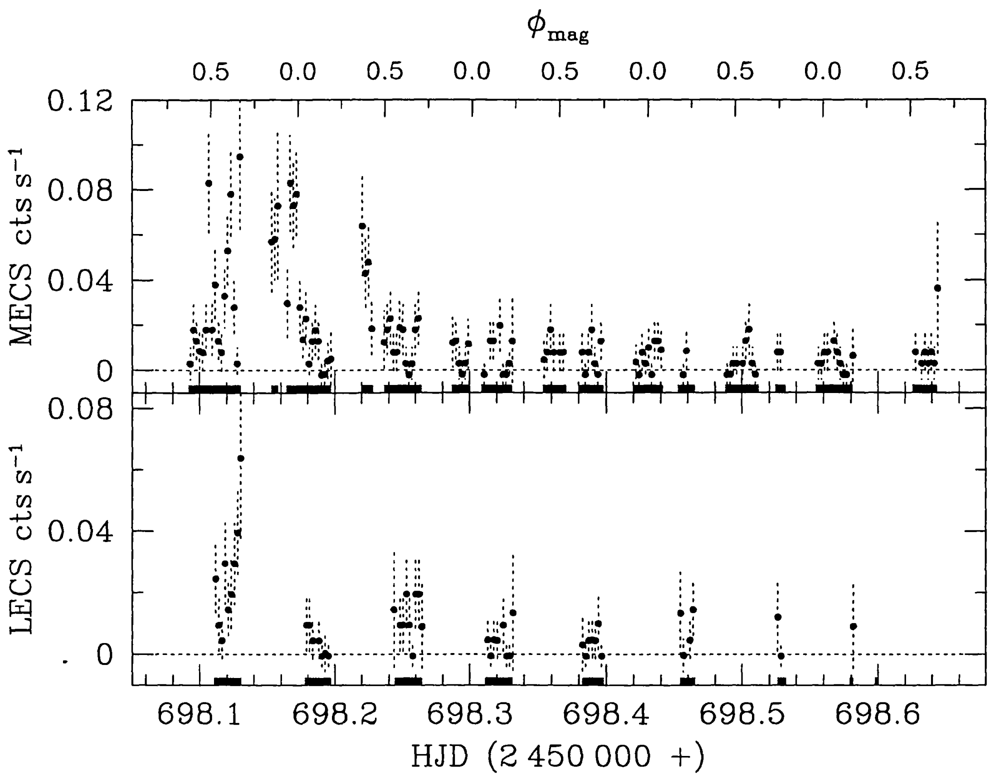

Figure 3. The net light curves of AM Her in September 1997 in the LECS (lower panel) and the MECS (upper panel) binned at 200 sec. The effective on-source times are marked as black areas. The top axis gives magnetic phases using the linear polarization ephemeris reported in Heise & Verbunt (1988).

At this time AM Her displayed erratic behaviour (Fig. 3) in both detectors, where count rates increased at the beginning of the observation by factors of ~ 7 and ~ 6 in the MECS and LECS respectively. A subsequent decay was observed. Despite the satellite orbital gaps, a second decay is also observed in the MECS. AM Her remained at a constant level afterwards but didn't switch off completely. The rise and decay have exponential characteristic times of $\tau_{\rm rise} = 44^{+46}_{-14}$ min and $\tau_{\rm fall} = 39^{+13}_{-8}$ min.

Separating this "active" phase, lasting ~ 4 hr since the start of the observation, from the subsequent "quiescent" period of ~ 9 hrs, the brightening occurs at orbital phases when the primary pole is visible (i.e. 0.3–0.9), while a deep minimum occurs between 0.1–0.2 corresponding to the eclipse of the primary pole. A second minimum, between phases 0.42 and 0.55, cannot be safely attributed to the dip features observed in the intermediate or high state light curves (see the detailed discussion in de Martino et al. 1998b). This dip is then very likely produced by intrinsic variations.

The active phase spectrum does not require a soft-X-ray blackbody as was also found during low state observations by *Einstein* (Fabbiano 1982) and *ROSAT* (Gänsicke et al. 1995). A Raymond-Smith model fit to the LECS+MECS spectrum of the active period, fixing $N_H = 9 \times 10^{19}\,cm^{-2}$ (Gänsicke et al. 1995) and abundances to the solar value, gives $kT = 5.8^{+3.9}_{-1.8}$ keV (see de Martino et al. 1998b for a detailed discussion).

A comparison with X-ray flare characteristics observed in active dMe and RS CVn stars (Pallavicini et al. 1990) shows that the timing of the observed activity in AM Her and the temperature are substantially different. The flare stars are characterized by very rapid increases and longer decays while temperatures are lower than 3 keV. Also, the energetics (1.4×10^{34} erg) and the inferred emission measure of $1.4 \times 10^{53}\,cm^{-3}$ are at the high end of stellar flares. This suggests that the observed event is most likely accretion induced. In this case a lower limit to the accretion luminosity of $2.4 \times 10^{31}\,erg\,s^{-1}$ is derived, implying $\dot{M} \geq 4 \times 10^{-12}\,M_\odot\,yr^{-1}$, which is consistent with the expected value from gravitational braking (Warner 1995).

The long 9-hr quiescence observed afterwards shows no substantial variations. For a Raymond-Smith model, fixing the hydrogen column density as above, a lower limit of $kT \geq 3.6$ keV to the optically thin plasma temperature is derived. Assuming the same temperature of the active phase, the bolometric flux is ~ 8 times lower than those observed during previous low states (Fabbiano 1982; Gänsicke et al. 1995). For $d = 91$ pc (Gänsicke et al. 1995), the bolometric luminosity of $\sim 5 \times 10^{29}\,erg\,s^{-1}$ is consistent with coronal emission, indicating a turn off of the mass transfer. However, the short timescale on which the accretion turns off is close to the dynamical timescale of the secondary star (Warner 1995), and the possibility of the secondary star detaching from the Roche lobe would require a longer timescale ~ 1 d (King & Cannizzo 1998). An alternative solution then could be that a giant eruptive mass ejection from the secondary star has triggered this event, although eruptive prominences in late type stars involve masses lower by a factor of ~ 10 (Cameron 1991).

4.2 The intermediate state of AM Her

In May 1998, AM Her was detected not only by the LECS (16.7 ksec) and the MECS (33.6 ksec) detectors at average count rates of $0.25\,s^{-1}$ and $0.22\,s^{-1}$, but also by the PDS detector at an average count rate of $7.5 \times 10^{-2}\,s^{-1}$ in the 15–30 keV range. At this time AM Her was ~ 25 times brighter than in the previous *BeppoSAX* observation of September 1997. The analysis of these data is in progress (Matt et al., in preparation) and very preliminary results are presented here.

The LECS hardness ratio [(0.5–2 kev)–(0.1–0.5 keV)]/[(0.1–0.5 keV)+(0.5–2 keV)] = +0.37 indicates that, at this epoch also, AM Her was not dominated by a soft component, as demonstrated by the combined LECS+MECS+PDS spectrum of the bright phase (see Matt, this volume).

All light curves show a dominance of the primary pole indicating that AM Her, active again, was in its normal accretion mode. The MECS and LECS light curves (Fig. 4) show a similar morphology to that observed dur-

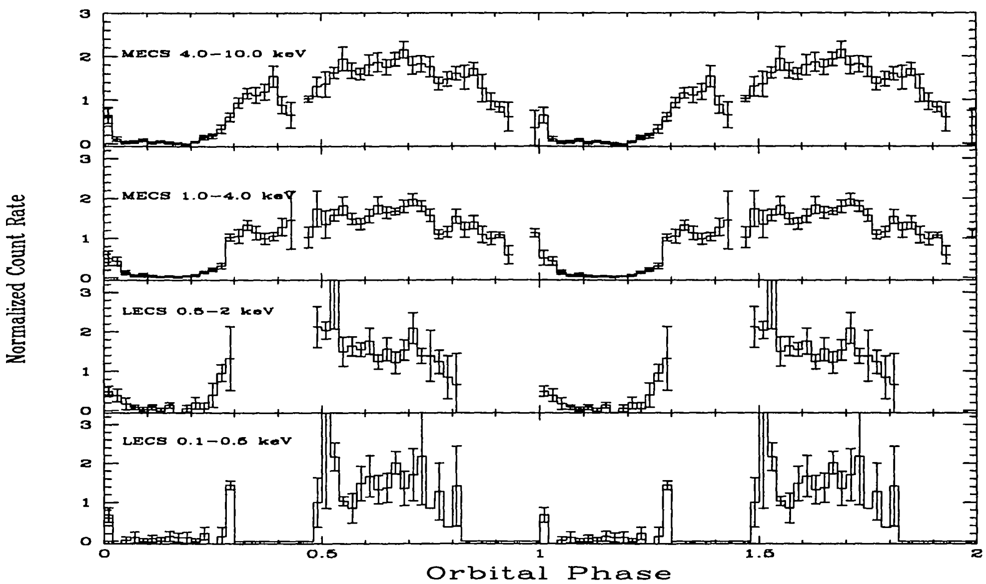

Figure 4. From top to bottom: the net folded light curves of AM Her in May 1998, in the MECS 4–10 keV and 1–4 keV bands and those of the LECS 0.5–2.0 keV and 0.1–0.5 keV bands binned at 50 sec. Ordinates are normalized counts.

ing high states with *ASCA* (Ishida et al. 1997) and *Ginga* (Beardmore & Osborne 1997). The average MECS hardness ratios [(4–10 keV)–(1–4 keV)]/[(1–4 keV)+(4–10 keV)] is –0.29 during the faint phase, while it is –0.08 during the bright phase. A softening during minimum is a recognized feature of high states.

5 Conclusions

The first *BeppoSAX* observations of three polars have revealed new insights into their variability and provided information on their X-ray emission components.

In BL Hyi during an intermediate-high state, the hard X-ray emission is observed from the secondary pole and found to be highly variable on timescales $\lesssim P_{\rm orb}$. The onset of accretion onto the secondary pole appears to depend on the luminosity level. The accretion on this pole is, however, highly unsteady.

The peculiar system V1309 Ori is found to display one of the most peculiar light curves in both soft and hard X-rays, characterized by an on/off flaring type activity. This system is also found to possess an extreme soft-to-hard X-ray flux ratio, representing an interesting case of "blobby" accretion which should account not only for the efficient soft X-ray emission but also for the hard X-ray production.

AM Her was caught during one of its longest and deepest low states. Transient activity related to enhanced accretion onto the primary pole has been found. This event was probably triggered by eruptive prominences from the secondary star. No soft X-ray component is found, compatible with a low accretion rate. Coronal emission from the secondary star is most likely the source of the quiescent X-ray flux indicating a switching off of the mass transfer rate from the secondary star. After ∼ 9 months of quiescence, AM Her returned active and in its normal accretion mode with no substantial soft X-ray component.

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Questions: Hessman spoke in favour of some of the observed X-ray emission in V1309 Ori coming from the secondary, noting that the fast-spinning secondaries could be more active than dMe stars, perhaps like T Tau stars. Eracleous, though, pointed out that rotationally-induced activity did saturate. Mauche reported the observation of an X-ray flare simultaneously with a He II flare from the secondary.