Astron. Astrophys. 332, 904–908 (1998)

ASTRONOMY AND ASTROPHYSICS

BeppoSAX observations of the long period polar system V1309 Ori⋆

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Received 22 October 1997 / Accepted 6 January 1998

Abstract. We present BeppoSAX observations of the peculiar long period polar system V1309 Ori (RXJ0515.6+0105). The source was detected simultaneously at soft and, for the first time, at hard X-rays with the LECS and the MECS detectors. Both, the LECS and the MECS light curves are irregular with a bursting/flaring type behaviour indicating inhomogeneous accretion onto the white dwarf. This peculiar variability, together with an extreme high soft-to-hard X-ray luminosity ratio, indicates that in V1309 Ori accretion occurs predominantly in highly compressed chunks or "blobs" of matter. From coordinated ESO optical spectroscopy, we find indications that the magnetic field strength of the white dwarf is < 70 MG, not expected either from the 8 hr orbital period synchronism or from the strong soft-to-hard X-ray ratio suggesting alternative solutions for sustaining synchronism in this system.

Key words: stars: individual: V1309 Ori= RXJ0515.6+0105 – cataclysmic variables – X-rays: stars

1. Introduction

Polars or AM Her stars are Cataclysmic Variables containing a synchronously rotating magnetic (B $\sim$ 10-230 MG) white dwarf accreting from a late-type secondary star. The strong magnetic field of the accreting white dwarf dominates the accretion flow and channels it towards the magnetic polar regions where a strong stand–off shock is produced. The hot post-shock plasma emits hard X-rays, partially absorbed and re-emitted from the surface at soft X-ray, EUV and UV wavelengths, as well as cyclotron emission which is observed at optical and IR wavelengths (Cropper 1990; Beuermann 1997). An independent soft X-ray component can be produced by the infall of dense plasma packets or blobs which penetrate deep into the atmosphere of the white dwarf and heat the photospere from below to a few 10^5 K (Kuijpers & Pringle 1982).

Polars have orbital periods in the range from 80 min to several hours, V1309 Ori being the longest period system with $P_{\rm orb} = 7.98$ hr. (Garnavich et al. 1994, Walter et al. 1995, Shafter et al. 1995, Buckley & Shafter 1995). V1309 Ori is an eclipsing polar showing a deep and variable primary minimum and a shallower secondary one (Garnavich et al. 1994, Shafter et al. 1995, Buckley & Shafter 1995). A magnetic field of $\leq$ 60MG was inferred from cyclotron features in the optical and IR and from optical polarimetry (Garnavich et al. 1994, Shafter et al. 1995, Buckley & Shafter 1995, Harrop-Allin et al 1997), although a higher magnetic field was expected for such a long period synchronous system.

The soft X-ray emission, as observed by ROSAT, is strongly variable on timescales down to few seconds in a bursting like activity, interpreted by Walter et al. (1995) as evidence for "blobby" accretion. The ROSAT data also indicated an X-ray variability at the $\sim$ 8 hr orbital period. Separate ROSAT pointings revealed that V1309 Ori shows, as most other polars do, a long-term variability in its X-ray flux due to changes in the mass transfer rate. The soft X-ray emission was found to be consistent with a black-body emission at 50 eV. No constraints on the hard component could be established from the ROSAT data. The extraordinary long orbital period of V1309 Ori makes it a key object to test theories for synchronization of the white dwarf while its pronounced short-term variability at X-ray wavelengths makes it a test case for the theory of "blobby" accretion.

In the framework of a program aiming to detect simultaneously the soft and hard X-ray emission in polars with the recent X-ray facility given by the BeppoSAX satellite, we present new X-ray observations of V1309 Ori obtained during the BeppoSAX AO1-Core Program together with coordinated optical spectroscopy collected at ESO.

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⋆ Also based on observations collected at the European Southern Observatory, La Silla, Chile

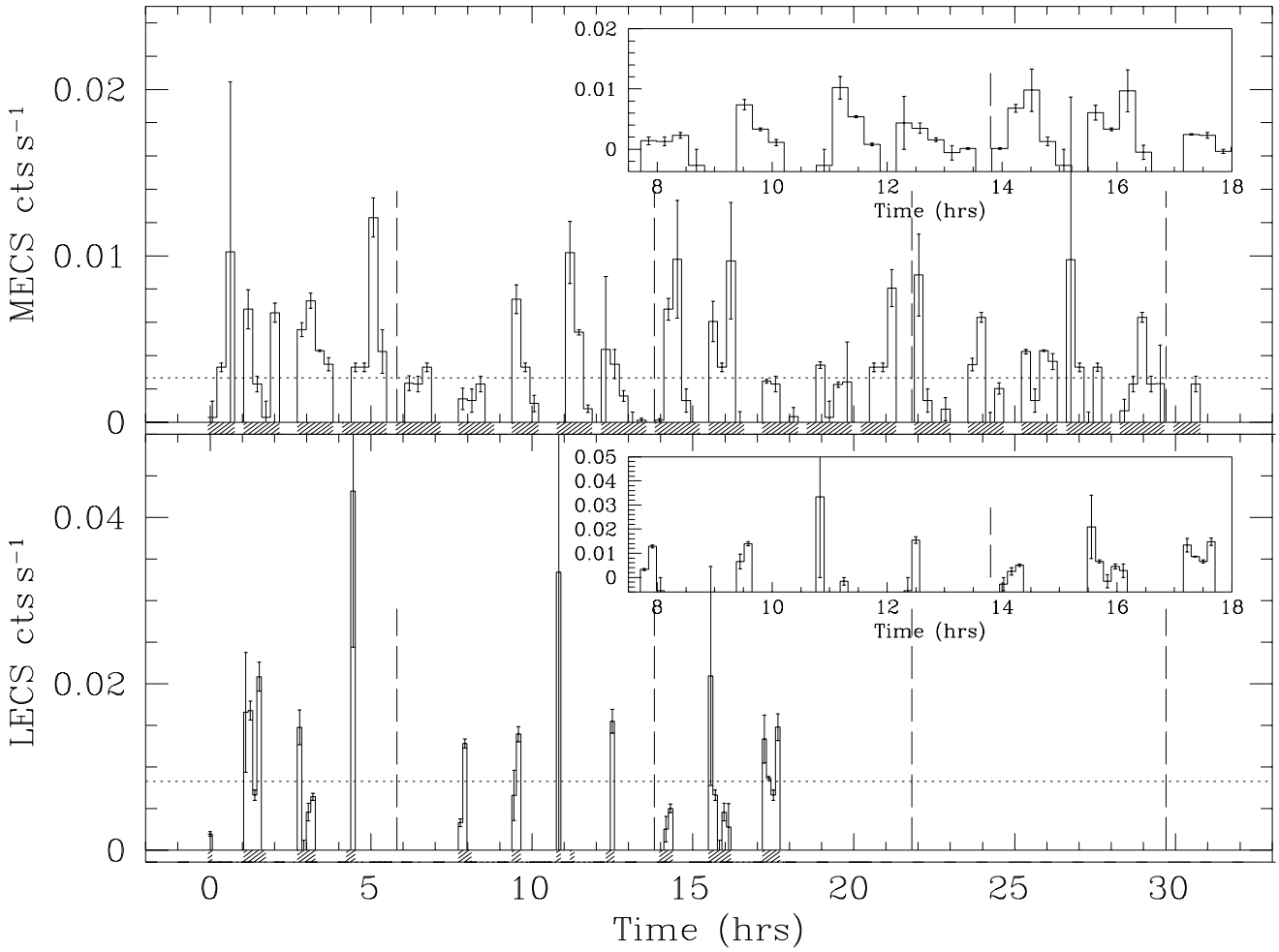

Fig. 1. The net light curves in the LECS (lower panel) and MECS (upper panel) detectors averaged in 500 sec and 1000 sec bins respectively. The mean count rates are also shown with a dashed line. Enlargements of are also reported in each panel where it is apparent that the source occasionally switches off in both detectors. The 98 min satellite orbital gaps as well as those related to LECS functioning are marked as shaded areas. The times of mid-eclipse using the refined ephemeris by Buckley & Shafter (1995) are marked with a dashed line. Note that counts below zero are due to the uniform background subtraction procedure.

2. BeppoSAX observations

The BeppoSAX X-ray satellite (Boella et al. 1997a) observed V1309 Ori on October 5 1996 with the set of the four co-aligned Narrow Fields Instruments (NFI), covering the wide energy range 0.1 - 300 keV, used as prime pointing instruments. The source has been detected only with the Low Energy Concentrator Spectrometer (LECS), a gas scintillator spectrometer covering the 0.1-10 keV energy range (see Parmar et al. 1997 for detailed description) and the three units of the Medium Energy Concentrator Spectrometers covering the 1.3-10 keV range (see Boella et al. 1997b). The source was not detected by the two high energy instruments, the HPGSPC (High Pressure Gas Scintillation Proportional Counter) and the PDS (Phoswich Detection System). Due to LECS instrumental problems and operational limitations during the satellite orbit, the resulting effective on–source exposure was 10ksec, whilst MECS observation, carried out without significant problems, resulted in an effective on–source exposure of ∼60ksec. In Table 1 we report the observation log.

Table 1. Journal of observations.

Instrument	Date - UT_{start} hh:mm	Date - UT_{end} hh:mm
LECS	1996 Oct.5 15:24	Oct.6 09:46
MECS	1996 Oct.5 15:24	Oct.6 22:15
ESO DFOSC	1996 Oct.7 08:58	09:18
ESO DFOSC	1996 Oct.8 04:56	05:21

LECS and MECS observations have been pre-processed at the BeppoSAX Software Data Center (SDC). The three MECS unit event files have been summed after equalization to unit 1. Hereafter the name MECS will refer to the sum of the three units.

LECS and MECS spectra and light curves have been extracted from circular regions with radii of 4' and 2' around the centroid source image respectively. Since the background in both instruments was found to be stable along the satellite orbit, it has been measured from blank sky pointings from the same regions of source count extraction. The average background count rates are $5.62 \pm 0.19 \cdot 10^{-3}$ cts s^{-1} and $2.71 \pm 0.08 \cdot 10^{-3}$ cts s^{-1} for LECS and MECS, respectively. Light curves and spectra have been extracted using the XSELECT package, while the XSPEC and XRONOS packages have been used to perform spectral and temporal analysis.

2.1. The X-ray light curves

LECS and MECS light curves are shown in Fig. 1 where the data have been binned in 500 s and 1000 s bins respectively. The average net count rate in LECS is $7.42 \pm 1.25 \cdot 10^{-3}$cts s^{-1} and $2.70 \pm 0.35 \cdot 10^{-3}$cts s^{-1} in MECS. As it will be discussed in par.2.2, the LECS detector is dominated by the soft X-ray component of V1309 Ori as also apparent from the hardness ratio [2-10 keV] - [0.1-2 keV] /[0.1-2 keV] + [2-10 keV] = -0.22. Thus MECS and LECS ligth curves are indicative of the variability in the hard and soft X-ray emissions respectively. In both light curves the source shows a flaring/bursting activity, as it is apparent from the enlargements reported in each panel. This peculiar behaviour is composed by discrete events interleaved by faint states and occasional switching off of the source. The source is $\sim 55 - 60\%$ of the time at a low level of emission. In these light curves the flaring activity has typical timescales ≤ 30 mins, consistent to that observed during previous ROSAT observations although the latter allowed the detection of variations on timescales down to few seconds (Walter et al. 1995). In these binned light curves the source is observed to vary by a factor up to 6 and to 3 in the LECS and MECS respectively with respect to the average level. Even though the poor coverage with the LECS detector prevents a statistical correlation study between the temporal behaviour of the soft and hard X-ray components, it is clear from Fig. 1, that the bursts/flares do not necessarily coincide in the two light curves. The low level of the source in the instruments prevents any study of the behaviour in the hardness ratios within each instrument energy bands so to ascribe a spectral trend to this peculiar variability. It is worth mentioning that these BeppoSAX observations do not reveal the 8 hr bursting periodicity as inferred from ROSAT data by Walter et al. (1995). Due to satellite orbital gaps and the low level of the source, which hampers a finer time binning of the data, we are unable to detect the eclipse of the white dwarf (Fig. 1).

2.2. The X-ray spectrum

The soft X-ray component of V1309 Ori was detected in the ROSAT band (Walter et al. 1995) but no constrains on the hard X-ray component could be found. The extension to higher energies than those covered by ROSAT (≥ 2 keV) allows the detection of the hard X-ray emission for the first time. The average X-ray composite LECS and MECS spectrum of V1309 Ori is shown in Fig. 2 together with a two component best fit consisting of a black-body kT$_{\rm bb}$ = 30^{+30}_{-21} eV and a Raymond-Smith (Raymond & Smith 1977) kT$_{\rm RS}$ = $10^{+\infty}_{-5}$ keV models, assuming solar abundances (A=1) (χ^2 = 20.6, Dof=25). The quoted errors are 90% confidence for one interesting parameter ($\Delta\chi^2$ = 2.7). The hydrogen column density is found to be 4 $\cdot 10^{20}$cm^{-2}, poorly constrained, but compatible with the value of $5.4 \pm 1.3 \cdot 10^{20}$cm^{-2}, found from ROSAT data (Walter et al. 1995). While ROSAT observations are consistent with a $\sim$ 50 eV black-body, we still find a 30eV temperature fixing N$_{\rm H}$ to $5.4 \cdot 10^{20}$cm^{-2}. With the derived spectral fits parameters, the measured flux in the 0.1-2 keV range is $5.8 \cdot 10^{-13}$erg cm^{-2} s^{-1} while in the 2-10 keV range it is $2.1 \cdot 10^{-13}$erg cm^{-2}s^{-1}. The black-body bolometric flux ranges between $2 - 5 \cdot 10^{-11}$erg cm^{-2}s^{-1} for kT$_{\rm bb}$ = 30 $-$ 50 eV and N$_{\rm H}$ = $4 - 5.4 \cdot 10^{20}$cm^{-2}. On the other hand, from the emission measure of the optically thin component at 10 keV, assuming a Gaunt factor of 1.2, we find a bolometric flux of $3.1 \pm 0.7 \cdot 10^{-13}$erg cm^{-2}s^{-1}. This implies a very high soft-to-hard X-ray ratio F$_{\rm bb}$/F$_{\rm RS}$ ranging between 65 and 160. We also compared the soft-to-hard flux ratio in V1309 Ori with those observed in other polars (Beuermann & Woelk 1996, Beuermann 1997) in the ROSAT band 0.1-2.4 keV. We fitted the BeppoSAX data adopting for the optically thin plasma a temperature of 20 keV, a 25 eV black-body and N$_{\rm H}$ to $4 \cdot 10^{20}$cm^{-2}, obtaining F$_{\rm bb}$/F$_{\rm RS}$ = 430, the highest ratio ever observed in any system.

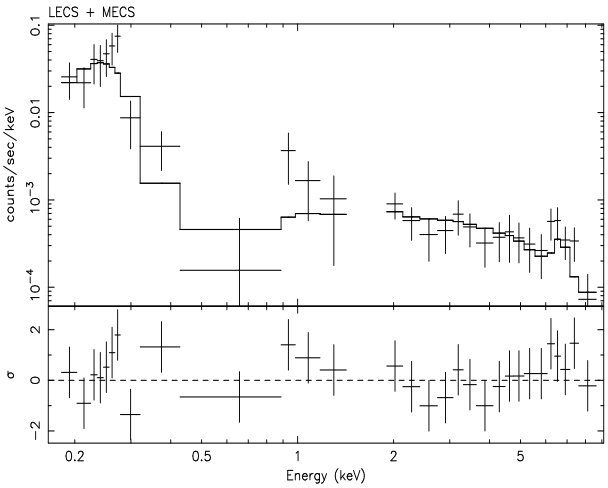

Fig. 2. Average MECS and LECS spectra together with the composite spectrum consisting of a 30 eV black-body and a 10 keV Raymond-Smith models. The excess of flux at 0.3 keV is likely due to the LECS calibration matrices.

We furthermore note that the hydrogen column density, as indicated by the ROSAT and our data, is much lower than the total interstellar galactic column in the direction of the source, $\sim 10^{21}$cm^{-2}, which would be expected from the distance estimate of 1.5 kpc (Harrop-Allin et al. 1997) and it is more compatible with a $\sim$ 500 pc distance as suggested by Buckley & Shafter (1995). The distance d of V1309 Ori can be inferred from the R band ratio of the observed brightness of the secondary star at mid-eclipse (given in Shafter et al. 1995) and the surface

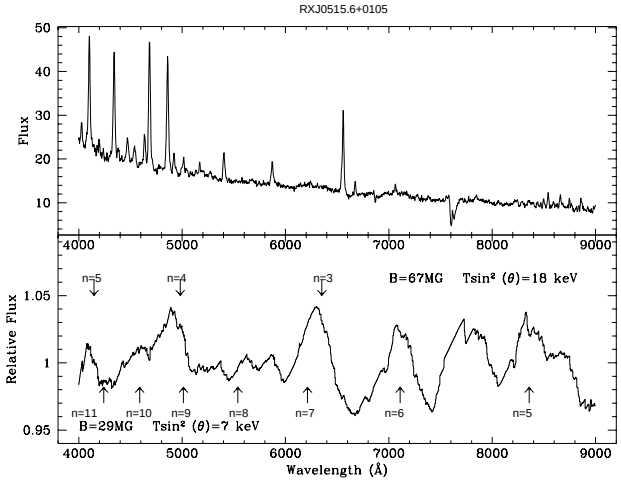

Fig. 3. Upper panel: The difference spectrum between spectra at 0.48 and 0.99 orbital phases. Ordinates are in units of $10^{-16}\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$. **Lower panel:** The smoothed normalized cyclotron spectrum and the expected positions for the two best solutions of B and $\mathrm{T}\sin^2(\theta)$ as described in the text.

brightness of an M0-1 star. As $\mathrm{d} \propto \mathrm{R}_2$ and the radius of the Roche-lobe filling star depends on its mass as $\mathrm{R}_2 \propto \mathrm{M}_2^{1/3}$, we find $\mathrm{d} \simeq 830\,(\mathrm{M}_2/\mathrm{M}_\odot)^{1/3}\,\mathrm{pc}$. The secondary star has driven out of thermal equilibrium (Frank et al. 1995) and while its temperature is that of an M0-1 star ($\sim 3800\,\mathrm{K}$), its luminosity and mass are not easy to estimate. We then consider a possible range for M_2 between 0.25 and $0.80\,\mathrm{M}_\odot$, which gives $\mathrm{d} \simeq 525 - 777\,\mathrm{pc}$. The distance of 1.5 kpc by Harrop-Allin (1997) then appears to be overestimated. For an average distance of 650 pc, the bolometric black-body luminosity is then $1 - 2.5 \cdot 10^{33}\mathrm{erg\,s^{-1}}$ and that of the thermal optically thin plasma is $1.6\pm0.4 \cdot 10^{31}\mathrm{erg\,s^{-1}}$.

3. The optical observations

Optical spectroscopy has been carried out on October 7/8, at the Danish 1.54m ESO telescope equipped with DFOSC+CCD/LORAL 2kx2k spectrograph configuration operated with grism 4 covering the range between 3550 and 9000 Å with a nominal dispersion of 220 Å $\mathrm{mm^{-1}}$. A slit of 2.5" has been used resulting into a 16.9 Å resolution, as measured from Ar-He arc calibration lines. Two spectra with exposures times of 20 min and 25 min have been acquired centred at phases 0.48 and 0.99 respectively, (using the refined eclipse ephemeris of Buckley & Shafter (1995)). Given the shape of the optical light curve (Garnavich et al. 1994), the spectrum at phase 0.48 falls on the egress phases of the secondary minimum. Data have been reduced using the MIDAS package for standard spectroscopic reduction procedures including bias, flat-fielding and wavelength calibration. The latter has been shifted using the sky line at 5577.4 Å to correct for deflections introduced by the telescope. The spectra have been extracted using the optimized method by Horne (1986). Flux calibration has been performed using observations of the standard star LTT 1788.

Both spectra are very similar in shape and intensity to those observed at phases 0.21 and 0.01 by Shafter et al. (1995). While the out-of-eclipse spectrum shows the strong Balmer, He II and He I emission lines characteristic of an AM Her star, the eclipse spectrum displays the secondary star absorption spectrum typical of a M0 dwarf (Garnavich et al. 1994, Buckley et al. 1995). In order to analyze the accretion induced spectrum we removed the latter component by subtracting the eclipse spectrum. We note that the secondary star absorption features, especially the TiO band at 7600 Å, are not completely removed. This difference spectrum, shown in the upper panel of Fig. 3, displays a strong ratio of $\mathrm{H}_\beta/\mathrm{H}_\alpha$=1.5 while $\mathrm{H}_\beta/\mathrm{H}_\gamma \sim 1$. Also, He II 4686 Å is similar in flux to that of H_β. In order to detect cyclotron features we removed strong and faint emission lines by means of gaussian fits while the residual secondary star absorptions have been excised interpolating the adjacent continuum. Here we note that the ellipsoidal modulation might introduce a bias or a systematic error in the cyclotron spectrum. It is expected that the contribution of the secondary star at the two phases is different. This can be additionally affected by X-ray heating which is however difficult to quantify. We estimate the difference in the optical flux of the two minima due to ellipsoidal variations neglecting at first approximation heating effects. Following the work of Bochkarev et al. (1979) for a mass ratio of 1 ($0.8 \leq \mathrm{q} \leq 1.4$ (Shafter et al. 1995)), a gravity darkening parameter β=0.25 (at optical wavelengths), a radius ratio of the secondary star to that of the polar Roche lobe between 0.9-1, an inclination angle of 90° and a limb darkening ranging between 0.6 to 1, the difference of the two minima ranges from 0.03 mag to a peak value of 0.16 mag. For an average value of 0.09 mag, this difference converts into an error of $\sim 2\%$ in the cyclotron flux. We then applied a median filtering and normalized the spectrum using a composite polynomial function fitted to the observed continuum. The resulting spectrum is shown in the lower panel of Fig. 3. Five weak features are detected which might be interpreted as cyclotron emissions. Although their detection is at the one sigma level, (the noise in this spectrum $\sim 4\%$), our spectrum is very similar in intensity to those derived by Garnavich et al. (1994) and Shafter et al. (1995) at other phases. In order to obtain estimates on the magnetic field strength and temperature $\mathrm{T}\sin^2(\theta)$ where T is the temperature in keV and θ is the viewing angle to the field lines (Cropper et al. 1989), we fitted the observed positions, but no consistent solution is found to explain all of them. Retaining the two strongest features at $\sim$ 4842Å and 6282 Å, we find B=67 $\pm$ 1 MG and $\mathrm{T}\sin^2(\theta) = 18\pm 1\,\mathrm{keV}$ (quoted errors are at 68% confidence). These features correspond to the 4^{th}(4912 Å) and 3^{rd}(6283 Å) harmonics respectively. On the other hand, a solution with B= 29$\pm$ 1 MG and $\mathrm{T}\sin^2(\theta) = 7\pm1\,\mathrm{keV}$ would account for the humps at 8357 Å, 7106 Å, and 6282 Å(n=5,6 and 7 respectively). This would also predict harmonics up to n=11, whose presence is rather difficult to assess (see Fig. 3). We note that the the broad hump at 7762 Å, which is very close to the secondary star absorption, is likely due to the removal procedure. The first solution matches with the results from optical spectroscopy and polarimetric observations of Buckley & Shafter (1995), Shafter

et al. (1995) and Harrop-Allin et al. (1997), while the second one is compatible with the low field estimate of 33 MG by Garnavich et al. (1994) (though they find a very low temperature). Although we cannot be conclusive given the method we used and the single spectrum we base our analysis on, we conservatively prefer the first solution of a 67 MG field white dwarf which accounts for the strongest humps. The lower field solution cannot be excluded, but, however, it needs further observational basis, i.e. higher S/N spectroscopy possibly at different orbital phases. These data, differently from Shafter et al.'s (1995) statement, give indication that cyclotron emission is present around secondary minimum.

4. Discussion and conclusions

During the BeppoSAX observations V1309 Ori was at a flux level comparable to that observed during one of the ROSAT pointings in 1991 when the source was found to be highly variable. A bursting-on/off behaviour, which can be decomposed in quiet intervals interleaved with strong flares, has been observed by BeppoSAX not only in the soft X-rays but also in the hard X-ray emission. Such variability indicates that the activity is due to occasional increases of accretion onto the white dwarf as also suggested by Walter et al. (1995). However the fact that the source sometimes switches off in both hard and soft X-rays is a strong indication of a highly inhomogeneous accretion. Although flaring activity has been observed in other polars like BL Hyi (Beuermann & Schwope 1989) and QS Tel (Rosen et al. 1996), V1309 Ori is the first system to show such a marked variability also in the hard X-rays.

Its X-ray spectrum consists of a soft and a hard component which can be described by a 30 eV black-body and a 10 keV optically thin plasma emission (Raymond-Smith model). This first detection of the hard X-ray component allows us to derive an extremely high soft-to-hard X-ray bolometric flux ratio of $\sim$ 65-160. Such a large soft X-ray excess indicates that in V1309 Ori most of the kinetic energy is emitted from a shock buried deep in the white dwarf atmosphere, at optical depths greater than one even in the hard X-rays. Radiation transfer then reprocesses the primary thermal bremsstrahlung into soft X-rays emitted from the surface. We estimate the mean accretion rate assuming that the bulk of the accretion luminosity is irradiated in the soft X-rays: $\mathrm{L_{bb}} = 1 - 2 \cdot 10^{33} \mathrm{erg\,s^{-1}} \sim \mathrm{G\dot{M}\,M_{wd}R_{wd}^{-1}}$. For a standard white dwarf of $0.6 M_{\odot}$ and a radius of $8{\cdot}10^{8}\mathrm{cm}$, $\dot{\mathrm{M}} = 1.5 - 3.2 \cdot 10^{-10} \mathrm{M_{\odot}\,yr^{-1}}$ which is within the observed range of other polars. A buried shock may form if the white dwarf in V1309 Ori possesses a very high magnetic field $\geq$ 150 MG and cyclotron cooling is so efficient that the stand–off shock collapses. Such a high field would be indicated by the 8 hr orbital synchronism for a 0.6 $\mathrm{M_{\odot}}$ white dwarf (Patterson 1994), but it is not confirmed by the observations (see below).

Another possibility is that the matter is accreted predominantly at high local mass flow rates in form of discrete blobs which penetrate deep in to the atmosphere of the white dwarf (Kuijpers & Pringle 1982). Considering that there is no observational evidence for an extremely high magnetic field and that the X-ray light curves display a strong bursting/flaring character, we favour the idea of "blobby" accretion to explain the soft X-ray excess in V1309 Ori. However, these BeppoSAX observations indicate that the conventional "blobby " accretion picture should be modified to account for blobs also to produce hard X-rays.

From optical spectroscopy and polarimetry a magnetic field strength up to 60 MG was derived (Garnavich et al. 1994, Buckley & Shafter 1995, Shafter et al. 1995, Harrop-Allin et al. 1997). Our optical spectrophotometry acquired during primary minimum and close to the secondary minimum, also suggests a magnetic field of $<$70 MG indicating a low field white dwarf, and thus suggesting different solutions to the mechanism of maintaining synchronism. Indeed Frank et al. (1995) proposed that synchronism in V1309 Ori can be sustained if the secondary star possesses a relatively high field ($\geq$ 1 kG). On the other hand a light white dwarf $\leq 0.47 M_{\odot}$ is required from the synchronism and for an upper limit of 70 MG as also suggested by Shafter et al. (1995). Is then possible that two mechanisms are occurring in V1309 Ori: the action of a higher field of the secondary star as proposed by Frank et al. (1995) as well as a lighter accreting white dwarf.

In summary, while our new X-ray observations indicate that V1309 Ori represents an extreme case of "blobby" accretion, the optical data support a relatively low field white dwarf thus making this system a test case for further detailed theoretical work.

Acknowledgements. We acknowledge BeppoSAX SDC team for providing pre-processed event files and for their constant support and advice in data reduction. GM acknowledges financial support from ASI.

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