X-RAY OBSERVATIONS OF CATACLYSMIC VARIABLES

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ABSTRACT

The X-ray observatory EXOSAT spent over 1000 hours observing cataclysmic variables. Some of the major results reviewed here are: soft X-ray light curve changes in AM Her objects, orbital effects in the X-ray light curves of intermediate polars and U Gem, regular behaviour in the inter-outburst X-ray flux of VW Hyi, and X-ray emission from the tenuous remnant of the recent recurrent nova RS Oph. The ability of EXOSAT to make long uninterupted observations at high sensitivity over a broad spectral range and to react quickly to cosmic events has yielded a dataset of a quality that will not be surpassed for many years.

INTRODUCTION

Cataclysmic variables (CVs) are binary systems in which a near main sequence star (occasionally a giant) loses mass via Roche lobe overflow to a white dwarf. In systems containing a white dwarf of low magnetic field, the transferred matter forms a disk which extends down to the surface of the white

Paper presented at the IAU Colloquium No. 93 on 'Cataclysmic Variables. Recent Multi-Frequency Observations and Theoretical Developments', held at Dr. Remeis-Sternwarte Bamberg, F.R.G., 16–19 June, 1986.

Astrophysics and Space Science **130** (1987) 207–223.

dwarf and is accreted at a low relative velocity. In systems containing more strongly magnetised non synchronously rotating white dwarfs, the inner edge of the disk is at a larger radius defined by the magnetosphere of the white dwarf. Inside this radius the accreted matter flows along the magnetic field lines, and thus radial accretion onto some fraction of the white dwarf surface occurs. These objects exhibit coherent X-ray pulsations at the rotation period of the white dwarf (which is less than the orbital period) and are known as Intermediate Polars or DQ Her objects, a pre-EXOSAT review is given by Warner (1985). CVs containing a magnetic white dwarf which is rotationally locked to the non degenerate star are known as AM Her objects or Polars. No accretion disk forms in these systems, the matter is funnelled by the magnetic field onto a very small fraction of the white dwarf surface causing X-ray emission which is observed to be modulated at the orbital period. Pre-EXOSAT reviews of our knowledege of AM Her objects are given by Liebert & Stockman (1985) and Lamb (1985).

EXOSAT (5/83 to 5/86) spent 10% of its time on CVs and was particularly well suited to the study of these objects. The 4 day orbital period allowed long uninterupted observations (typically 6.5 hours). This was a major advance over previous X-ray astronomy satellites all of which had low earth orbits with periods of around 90 minutes, close to the orbital period of the majority of the magnetic CVs.

The EXOSAT observatory had a sophisticated real time data analysis system and the flexibility to alter the observing schedule at short notice. Thus CV outbursts could be observed soon after they had started and could be followed up if they appeared interesting.

The two main detectors used in observations of CVs were the Medium Energy detector (ME), a high quality proportional counter array covering 1-10 keV with ~750 cm^2 each to monitor the source and the background; and the Low Energy imaging telescope (LE) which used filters in front of a channel multiplier array to determine the broad band colours of soft X-ray sources (0.04-2.0 keV). Although the LE had only ~10 cm^2, its low background and good low energy response made it a sensitive device which allowed the detection of low temperature spectral components. These instruments have been described in detail by de Korte et al. (1981) and Turner, Smith & Zimmerman (1981). Observations of CVs made in the first year of EXOSAT operations have been reviewed by Mason (1985).

AM HER OBJECTS

The standard model of accretion in AM Her objects is that of Lamb & Masters (1979). Hard X-rays come from shock heated material in the magnetically confined accretion column above the white dwarf. Infrared/ optical cyclotron emission also occurs here. The adjacent regions of the white dwarf are heated by these spectral components and emit a soft X-ray blackbody spectrum.

All except one of the known AM Her objects were observed by EXOSAT, most on more than one occasion and most with simultaneous optical observations. The majority of this data has not yet appeared in the literature.

Early EXOSAT observations of AM Her objects showed them to be bright soft

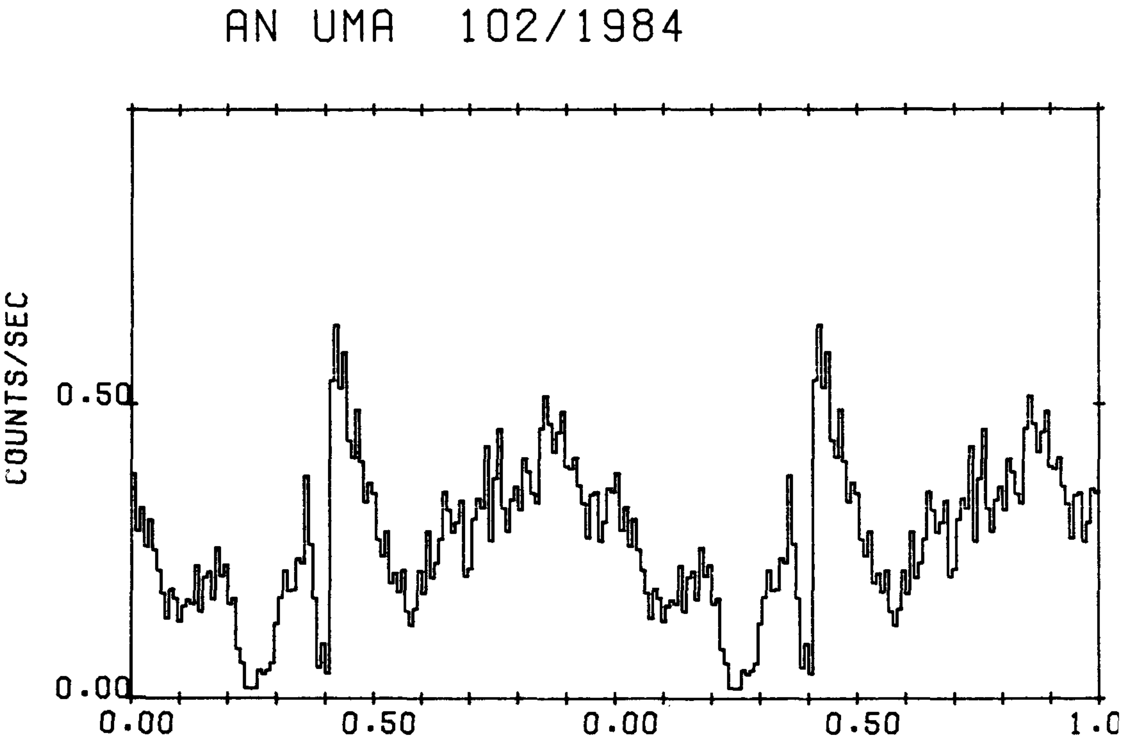

Figure 1. The soft X-ray (3000 lexan) light curve of the AM Her object AN UMa (P_{orb}=115 min) plotted against linear polarisation phase (ephemeris due to Liebert et al. 1982). Three consecutive orbits are folded here, all major features are present in the individual orbits. Note that the phasing is shifted by 0.3 P_{orb} with respect to the SAS 3 light curve of Hearn & Marshall (1979)

X-ray sources but generaly weak in the ME. The orbital light curves of the systems in which the accreting pole is in the distant hemisphere of the white dwarf (eg. VV Pup, CW1103+254) were, as expected, essentially undetectable when the the pole was hidden by the body of the white dwarf, but rapidly becoming bright when the pole appeared around the limb (Osborne et al. 1985a, Beuermann & Stella 1985). The asymmetric light curve of CW1103+254 has been interpreted in terms of an extended accretion region on the white dwarf (Beuermann 1986). A similar asymmetry is seen in VV Pup.

For systems in which the accretion pole remains continuosly in view (eg. E1405-451, E2003+225, AN UMa) the first EXOSAT soft X-ray light curves were surprising. They consisted of a broad hump lasting half an orbit followed by a narrower hump which was cut by two narrow eclipses, the first being broader than the second (Osborne et al. 1985a). As an example, the folded light curve of AN UMa is shown in figure 1. The expected soft X-ray light curve, due to the simple variation of the projected area of a single small bright spot on the surface of the white dwarf would be cosine-like, quite different to that seen.

The origin of the overall modulation is unknown. Invoking emission from another pole is difficult to justify as there is no evidence for this at other wavelengths. The low energy of the photons that go to make up these light curves suggests that they would easily be absorbed by small amounts of cool matter in the binary system. However, Osborne et al. (1986a), using the 500 line/mm soft X-ray diffraction grating on EXOSAT, have shown that for E2003+225 there is insufficient hardness ratio variation in the light curve to

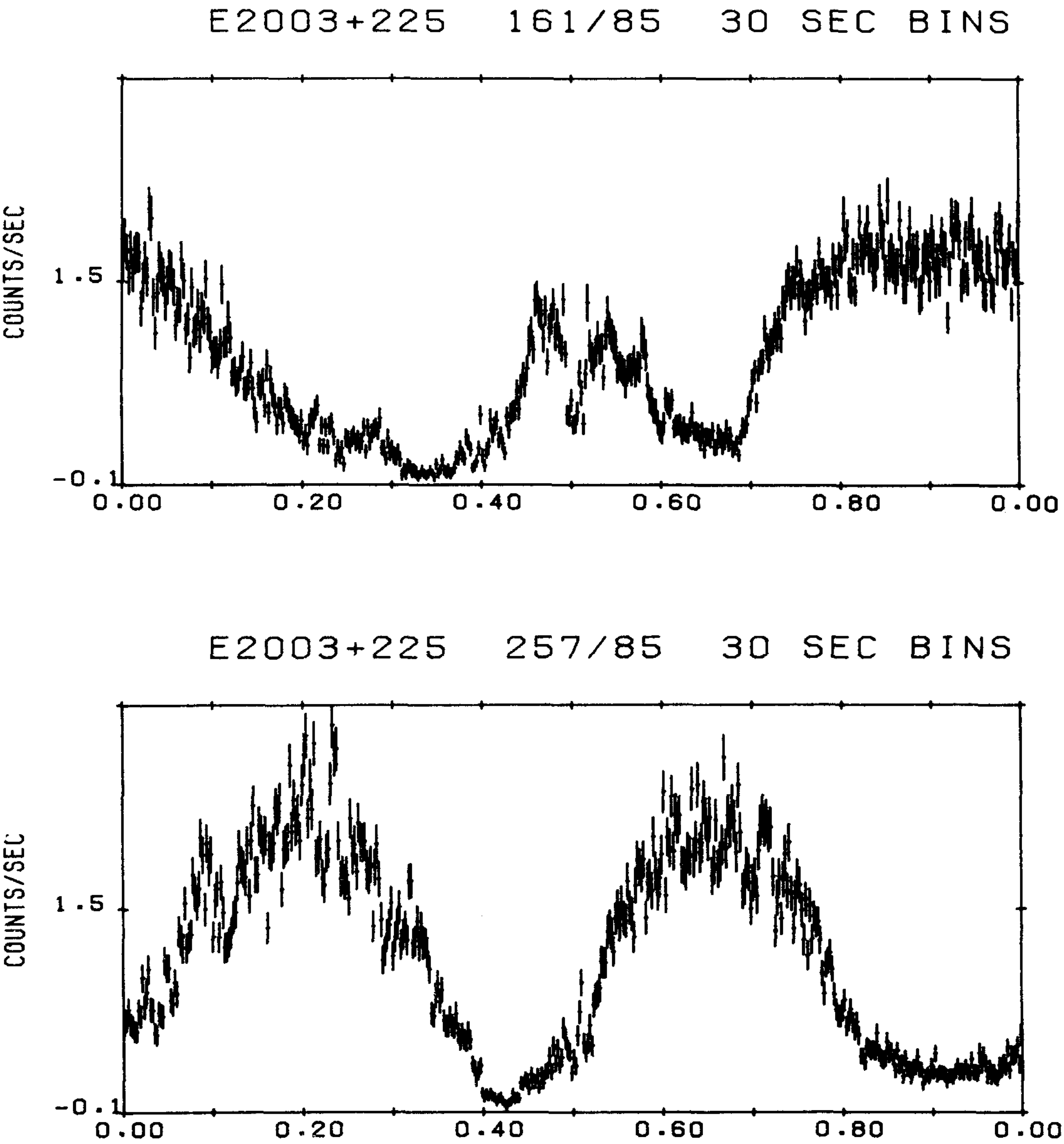

Figure 2. Two $5P_{orb}$ EXOSAT observations of the soft X-ray light curve of the AM Her object E2003+225 (P_{orb}=223 min) taken 96 days apart, folded and plotted against linear polarisation phase (ephemeris and light curves from Osborne et al. 1986b). Note the dramatic change in the form of these light curves and the phase shift of the eclipse. Previous X-ray observations of this source show it to have had a light curve similar to that in the top panel.

allow this explanation.

The eclipses could in principle be due to a number of reasons. Self-eclipse by the white dwarf is not likely in these cases as a linear polarisation pulse is expected at one or both eclipse edges, whereas the eclipses are observed between linear polarisation phases 0.25 and 0.55. Also, such eclipses could be expected to show a gradual ingress and egress as the projected area of the hot spot changed. Eclipse by the companion star is thought to occur in E1114-1182 (Biermann et al. 1985), where the optical eclipse is greater than 4 magnitudes. No such deep eclipse is seen in any other system. Much more likely as an explanation for at least one of the observed eclipses in each of these systems is absorption by the accretion flow as it rises out of the orbital plane before falling onto the white dwarf. Such an eclipse requires that the system inclination be greater than the angle between the rotational and magnetic axes of the white dwarf, as is confirmed by the polarisation studies of Brainerd & Lamb (1985). A similar origin was suggested for the X-ray eclipse in 2A0311-227 by Patterson, Williams & Hiltner (1981). Why there should sometimes be two eclipses in the soft X-ray light curves is not clear.

Later observations of E2003+225 (Osborne et al. 1986b) and E1405-451 (Osborne, Cropper & Cristiani 1986) provided more surprises. They showed that both sources could dramatically change the overall shape of their soft X-ray light curves to be essentially that expected for these objects, ie. a cosine cut by a single deep eclipse. This is illustrated for E2003+225 in figure 2. There was a coincident ~0.1 P_{orb} phase retardation of the eclipse in both of these cases, suggesting that the precise magnetic azimuth of the mass transfer stream is an important factor. In both these cases the soft X-ray light curve changes were associated with only minor optical light curve changes.

Changes in the soft X-ray light curves of AM Her objects were not known to occur prior to EXOSAT, however there are now reports of major changes in the soft X-ray light curves of H0139-68, E2003+225, E1405-451 and AM Her itself (Beuermann et al. 1985; Priedhorsky, Marshal & Hearn 1986; Heise et al. 1985; and refs above). The new mode of emission in AM Her is interpreted as due to an extra accreting pole, the two poles having very different soft X-ray to hard X-ray brightness ratios.

One of the main predictions of the theory of accretion in AM Her objects is that the soft X-rays arise from the reprocessing of the hard X-rays, thus there will be a strong positive correlation between the hard and soft X-ray flux with very little time lag. Stella, Beuermann and Patterson (1986) have shown from EINSTEIN data that whereas the hard and soft X-ray fluxes do show the same variability timescales, they are not correlated at zero time lag. These authors were also led to propose two emitting poles, one producing primarily hard X-rays and the other mainly soft X-rays.

INTERMEDIATE POLARS

The first task of some EXOSAT observations of intermediate polars was the determination of the white dwarf rotation period. This is difficult to do at optical wavelengths because it is not easy to distinguish pulses due to reprocessing of X-rays on (say) the companion or accretion disk from those

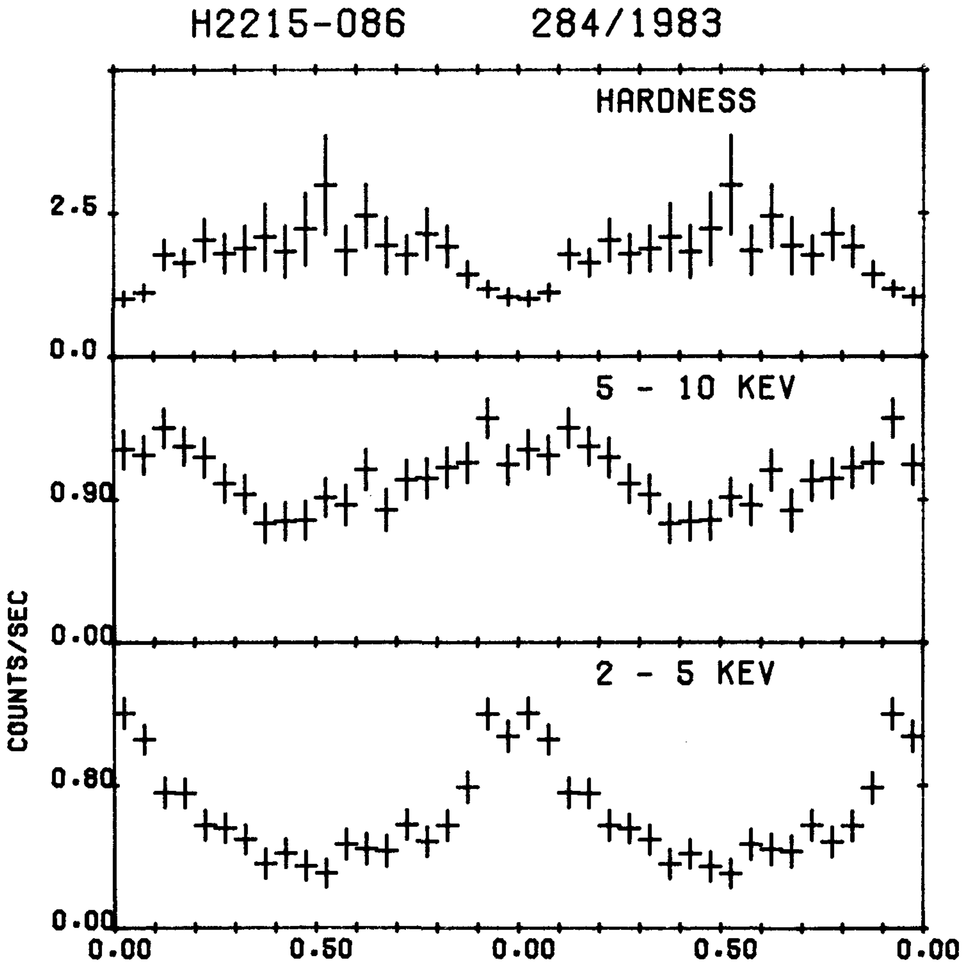

Figure 3. Seven hours of ME data of the intermediate polar H2215-086 folded at the X-ray period of 20.9 mins (the same as the optical period). The form of the spectral variation seen here is a major characteristic of these objects. Taken from Osborne et al. (1985b).

directly due to the rotation of the white dwarf. EXOSAT has been used to measure for the first time the X-ray pulsation periods of V1223 Sgr (12.4 min. Osborne et al. 1985b), H2215-086 (20.7 min. Cook, Watson & McHardy 1984) and 2A0526-328 (31.9 min. Schrijver, Brinkman & van der Woerd 1985). Of course X-ray observations are also a good technique for identifing CVs as intermediate polars, EXOSAT observations have been responsible for the suggestion that GK Per (P_{pulse}=5.85 min. Watson, King & Osborne 1985), 1H0542-407 (~33 min. Tuohy et al. 1985), V426 Oph (60 min. Szkody 1986) and SW UMa (15.9 min. Shafter, Szkody & Thorstensen 1986) are intermediate polars.

Observations of a number of these objects have revealed orbital modulation of the X-ray flux. EX Hya exhibits a partial X-ray eclipse at the time of the optical eclipse (Beuermann & Osborne 1985, Cordova, Mason & Kahn 1985) strongly suggesting an extended or multiple X-ray emission site. This source also shows a smooth orbital modulation at the lowest energies, the minimum leads the eclipse by 0.2 in phase and is presumably due to absorption in the disk-stream interaction bulge. Orbital modulation with a high duty cycle is also seen in 2A0526-328 (TV Col), SW UMa, H2252-035 (AO Psc) and possibly V1223 Sgr. One of the best studied is H2252-035 (Pietsch et al. 1986) which shows an absorption profile which is variable from day to day and which is associated with a simple increase in cold absorbing material. It is surprising that probably all of the intermediate polars for which suitable EXOSAT observations exist show orbital modulation, unfortunately the inclinations of the majority of those systems is unknown.

Spectral variation is also associated with the pulsations due to the white dwarf rotation, the pulsations are invariably softer than the average spectrum of the source (eg. Osborne et al. 1985b). This is illustrated in figure 3 for H2215-086. This variation is possibly due to the varying absorption as our viewing angle of the accreting region changes as the white dwarf rotates, or may be due to temperature structure in the accretion column. Phase resolved spectroscopy of H2252-035 suggests that the former explanation is sufficient (Pietsch et al. 1986), whereas EX Hya and V1223 Sgr require more complex spectral models to fit their on-pulse spectra.

CATACLYSMIC VARIABLES NOT EXHIBITING COHERENT X-RAY PULSATIONS

In this section I review the objects in which the magnetic field is not so dominant as to control the accretion flow. However, the existence of quasi periodic soft X-ray pulsations in SS Cyg, U Gem and VW Hyi suggests that significant magnetic fields exist in some of these objects (King 1985).

An observation of SS Cyg in quiescence early in the EXOSAT mission showed a flaring behaviour in which the intensity of the hard X-rays varied approximately as the square of the spectral temperature (King, Watson & Heise 1985). A later series of observations of the source in outburst showed an increase in soft X-rays and a decrease, without a change in the spectrum, in hard X-rays (Watson, King & Heise 1985); a pattern of behaviour noted previously in this source and in U Gem (Cordova & Mason 1983). Such observations have been taken as strong evidence in favour of the model of King & Shaviv (1984) in which the quiescent X-ray emission of a non-magnetic CV is attributed to a radiatively cooling hydrostatic corona around the white dwarf. The luminosity-temperature relationship of $L_X \alpha T^{1.5+2\epsilon}$ (ϵ small and positive)

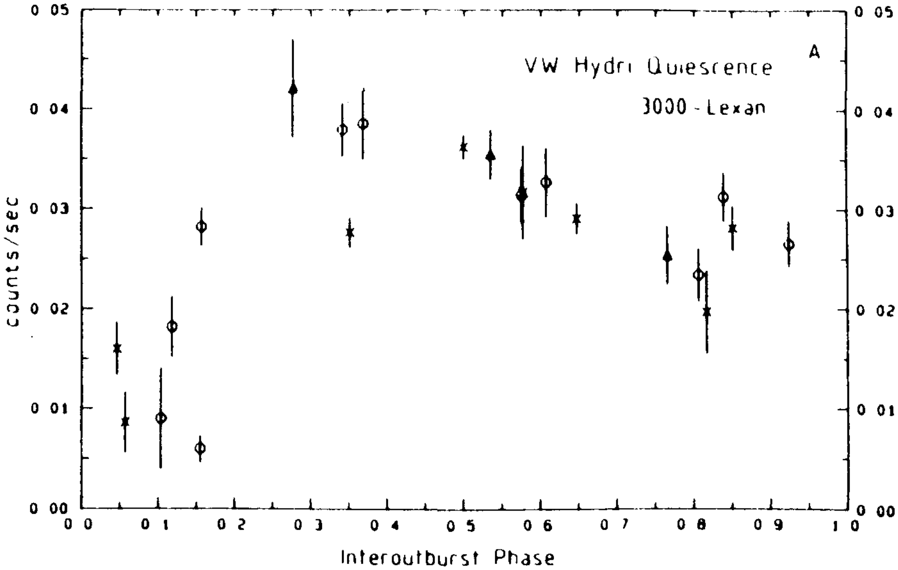

Figure 4. The behaviour of the X-ray flux of VW Hyi between outbursts. Data are from LE (3000 lexan) measurements of the hard X-ray component and are plotted relative to the moments of past and future outbursts. The different symbols refer to different epochs. From van der Woerd & Heise (1986).

predicted by this model derives from bremsstrahlung cooling of this corona. The hot corona forms because the accreting gas is unable to cool sufficiently rapidly at the low mass transfer densities associated with quiescence. It is thought to be supressed at higher accretion rates (flow densities) by more efficient optically thick boundary layer emission at XUV/ soft X-ray temperatures.

An observation of VW Hyi during superoutburst has shown a similar

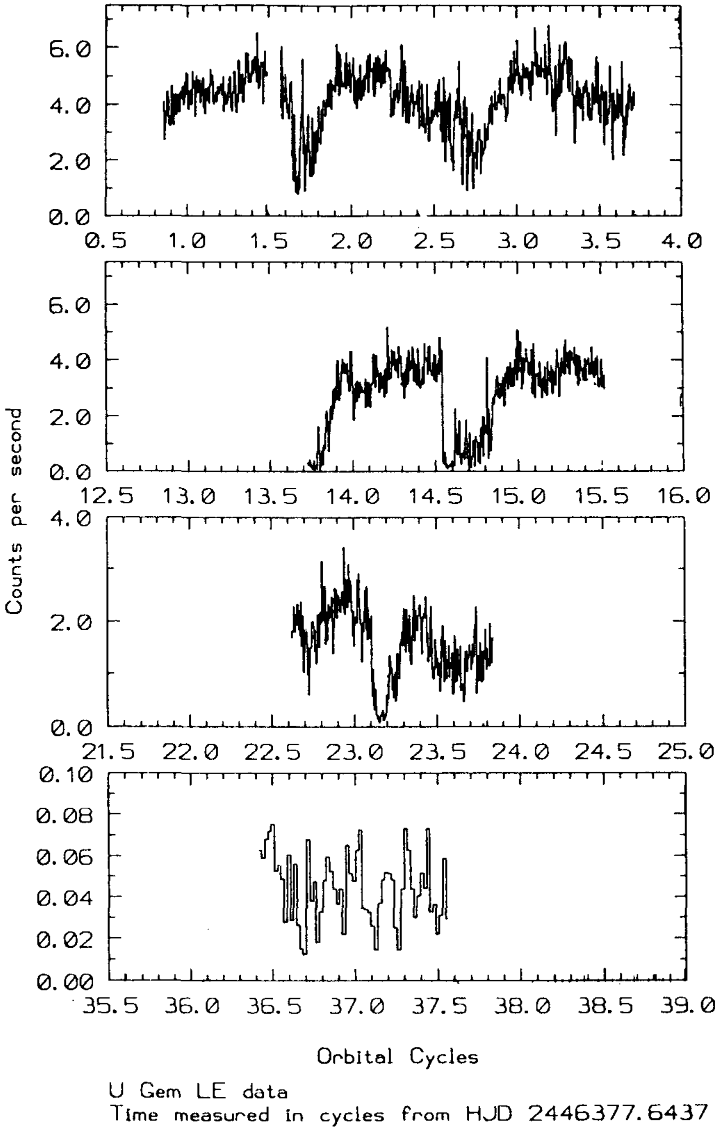

Figure 5. The soft X-ray (3000 lexan) flux of U Gem during the 1985 outburst plotted against eclipse phase (eclipse of disc bright spot defines phase zero). Note the changing profile and relative depths of the dips which are almost certainly due to photoelectric absorption in the locally raised accretion disk rim. The outburst had ended by the time of the last EXOSAT observation. From K. Mason.

transition from hard quiescent to soft outburst spectrum (van der Woerd, Heise & Bateson 1986). This object has been observed through normal outbursts, superoutburst and quiescence by van der Woerd & Heise (1986). They find a consistent pattern in the hard X-ray component flux between outbursts, dropping below the mean quiescent value for ~3 days after outburst then jumping up by a factor of 3-4 to then decline gradually until the next outburst (see figure 4), implying a factor of two decline in accretion rate between outbursts.

VW Hyi and other CVs usually have a half to one day delay between the start of the optical and the start of the EUV outbursts. The observation of van der Woerd, Heise & Bateson was unusual in that the X-ray outburst was apparently 2.5 days later than the optical outburst. The observations of a second superoutburst showed that a precursor event occurred. This was seen both by EXOSAT and Voyager (in the EUV). Fifteen hours after this the X-ray flux was back down to the quiescent level. It was seen at superoutburst level 2.7 days later. The existence of such precursors with a delayed X-ray/EUV rise to superoutburst was not previously known, and may provide important clues about the outburst phenomenon.

The 14.06 second soft X-ray pulsation observed by van der Woerd, Heise & Paerels (reported by Mason 1985) during the 1983 superoutburst can now be identified as a quasi periodic oscillation similar to that seen by EXOSAT in SS Cyg (Watson, King & Heise 1985). Observation of VW Hyi during the later superoutburst revealed a much less coherent soft X-ray pulsation with a period of 14.2 - 14.4 seconds (van der Woerd, priv. comm.).

U Geminorum was also studied with EXOSAT towards the end of the recent very long outburst. This object is known to produce an intense flux of very soft X-rays (kT_{BB}~25eV) during outbursts (Cordova et al. 1984). The soft X-ray light curve (supplied by K. Mason, figure 5) shows massive dips occurring twice per orbit. The dips show internal structure and vary considerably between the observations (which were separated by 2 days, ie. ~10 orbits). The last observation during the outburst shows that the dip centered on phase 0.7 had broadened to such an extent that it influenced the light curve throughout the whole orbital period, while the minor dip at phase ~0.05 has shifted to phase 0.15 and become almost total. These dips are almost certainly due to the accretion disk bulge at the stream impact points, such as is seen in some Low Mass X-ray Binaries (LMXRB White & Mason 1985) and some of the intermediate polars (see above). Variable depth, internal structure and dips seperated by about half an orbital period are all seen in the LMXRB.

EXOSAT observations of the recurrent nova RS Oph during its 1985 outburst have provided a picture of an object more like a supernova remnant than a CV. Mason et al. (1986) describe the evolution of the soft X-ray emission seen from 54 to 250 days after the outburst. This bright source was seen to decline slowly at first then more rapidly from ~60 days after outburst. No rapid variability or flickering was observed. The initial decline is consistent with emission from gas heated by a blast wave expanding into the pre-existing stellar wind of the red giant companion (Bode & Kahn 1985). The later fall off in intensity is interpreted as due to the blast having reached the outer limits of this relatively dense wind, thus having little more gas to heat.

I thank those who supplied material for this review prior to publication.

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