X-RAY EMISSION FROM CATACLYSMIC VARIABLES

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ABSTRACT. EXOSAT results on cataclysmic variables are reviewed. The long continuous X-ray observations afforded by this observatory, coupled with the sensitivity of its instruments to medium energy and very low energy X-rays, have enabled the rotational and orbital X-ray light curves of these stars to be measured in unprecedented detail. Examples are given of data on synchronously and asynchronously rotating magnetic systems, and on disc accreting stars. The impact of the new observations on our understanding of cataclysmic variables is discussed.

1. INTRODUCTION

Cataclysmic Variables (CV) are semi-detatched binary systems which contain a white dwarf that is accreting matter from a late-type companion. CV as a class can exhibit a rich variety of temporal phenomena. These include coherent and quasi-coherent pulsations, orbitally related variations, optical polarisation, short-term irregular brightenings (outbursts), long term high and low states and nova explosions. The CV are traditionally classified based on their optical properties into various sub-types which include the dwarf novae, classical novae, recurrent novae and nova-like systems. To these must be added the recently recognised class of magnetic variables. It is becoming increasingly clear, however, that a variety of phenomena transcend these classification boundaries, and that the cataclysmic variables are a more homogenous collection of objects than perhaps early groupings would have suggested.

Much of the recent progress in our understanding of CV has come about, either directly or indirectly, as a result of observations at energies above the optical band, particularly in the X-ray and ultraviolet spectral regions. It is the X-ray observations that I want to concentrate on in this paper, and particularly recent advances made using the European X-ray Astronomy satellite EXOSAT. To provide a framework for discussing the new results, I begin by summarising the major characteristics of CV in the X-ray band.

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2. X-RAY PROPERTIES OF CV

In the X-ray band the plethora of CV subtypes can be usefully reduced to just three, the X-ray properties being determined by the strength of white dwarf's magnetic field compared to the rate of mass-accretion, and the influence the field exerts on the flow of accreting material.

2.1 Weak Field

If the magnetic field of the white dwarf is weak, material overflowing the Roche lobe of the companion star forms into a disk (the accretion disk) around the compact star which penetrates all the way to the stellar surface. X-radiation is believed to be generated when rapidly orbiting inner disk material liberates its excess kinetic energy so as to settle onto the surface of the (more slowly rotating) white dwarf. It does so in a series of weak shocks (Pringle and Savonije 1979) or viscous interactions (Tylenda 1981). Some of the gas heated in this 'boundary layer' expands to form a hot (~10 keV) optically thin, X-ray emitting atmosphere about the compact star, particularly at low accretion rates. However, the oblique geometry of the boundary layer interaction is not particularly efficient at producing high temperature gas, so the fraction of the total accretion energy liberated as hard X-rays in the disk systems is usually quite low. Most of the accretion energy heats the inner disk and/or the surface layers of the white dwarf which (probably) re-radiate primarily in the EUV. When the accretion rate is high, the radiation is hot enough, and the interstellar absorbing column low enough, in some stars for the high energy tail of this emission to be detectable in the soft X-ray band (eg. Cordova and Mason 1983). A characteristic of this ultra-soft X-radiation is high amplitude pulsations which have been detected with various values of coherence.

2.2 The Rotating Magnetic Stars

The white dwarf in a number of CV systems possesses a magnetic field strong enough to disrupt the accretion disk before it reaches the stellar surface. The radial distance from the white dwarf at which the disk is disrupted depends on the balance between magnetic and gas pressure, and hence on the accretion rate as well as the magnetic field strength. Once the disk is disrupted, the accretion flow is channeled pseudo-radially onto the magnetic poles of the white dwarf, and liberates its kinetic energy in a shocked region above the magnetic polar cap. Because the accreting gas collides with the stellar surface 'head-on', this mechanism is very efficient at producing high temperature gas, and these stars are comparitively strong emitters of 2-10 keV X-rays. If the magnetic axis of the white dwarf is offset from its rotation axis, the aspect of the X-ray 'hot-spot', and thus the amount of X-ray emission detected, is modulated at the rotation period of the star. The white dwarf rotation period is also sometimes detected in the optical band, but often more prominent is the beat between the rotation period of the white dwarf and the orbital period of the binary.

This beat period arises because of reprocessing of X-radiation in a region (perhaps the companion star, or a bulge on the accretion disk) which is fixed in the frame of reference of the binary.

The rotating magnetic stars have been referred to as "Intermediate Polars" or "DQ Her" stars in the literature. Both terms have been critisised; the first because they are not Polars (i.e. they show no detectable optical polarization) and because it is not clear in what sense they are "intermediate"; the second because of doubts that DQ Her is a true member of the class. Accordingly, in this paper I shall refer to rotating magnetic CV by the more descriptive term ROMAR (for ROtating MAgnetic staR).

2.3 The Phase-locked Magnetic Stars

There are a number of cataclysmic variables in which the magnetic field of the white dwarf completely dominates the accretion flow and prevents any substantial accretion disk from forming. In these systems, known as the AM Her stars, or Polars because of their polarised optical emission, the rotation of the white dwarf is phase-locked to the binary period and material from the companion star is directly funnelled onto one or more of the magnetic poles of the compact star. Because the accretion flow is pseudo-radial, these stars, like the Romars, are relatively efficient producers of 2-10 keV X-rays. Also a feature of the Polars is strong ultra-soft X-ray emission which is apparently the high energy tail of an energetic extreme ultraviolet spectral component. The EUV emission is believed to arise in the heated surface of the white dwarf beneath the polar cap. Because the main source of emission in AM Her stars is comparitively small at all wavelengths (the shocked region of the accretion column above the polar cap, and its immediate environs) it is subject to geometric obscuration. Consequently a property of most AM Her stars is a complex light curve with features that may include, for example, self obscuration by the accretion column, obscuration by the main body of the white dwarf and perhaps occultation by the companion star. The possibility that more than one pole of the white dwarf can emit further complicates the interpretation of these light curves.

3. EXOSAT OBSERVATIONS OF CV

The ability of EXOSAT to make long, continuous observations of celestial objects is particularly valuable in sampling the the orbital or rotational modulations of CV; these are typically in the range 1 to 7 hours, and a few tens of minutes, respectively. Complete X-ray light curves can be obtained for the first time, and new examples of periodic phenomena can be searched for unhindered by gaps in the data. The large collecting area of the medium energy detector array on EXOSAT provides sensitivity to the comparatively weak hard X-ray emission of CV, while the extended low-energy response of the CMA detector on the low-energy telescopes is suited to the study of the intense soft X-ray/EUV emission components detected in many of these systems. These advantages make

EXOSAT a powerful tool for the study of CV X-ray emission, and in the following I discuss examples of some of the work already done. More detailed discussions of some individual stars can be found in the contributed papers.

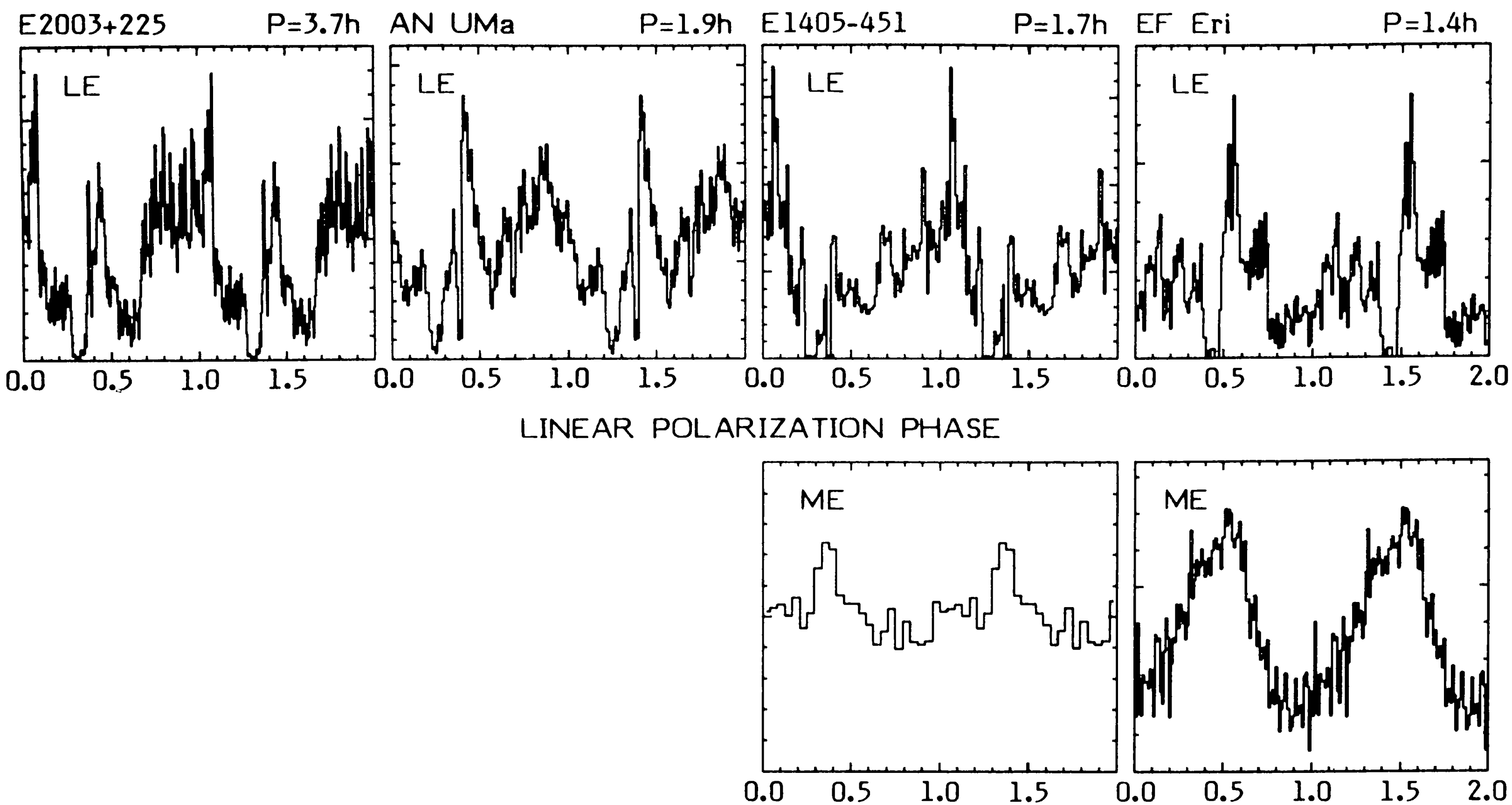
3.1 Polars (AM Her Stars)

The X-ray light curves of a number of polars, including E2003+225, AN UMa, E1405-451, VV Pup (Osborne et al. 1984a), EF Eri (Watson and King 1984, private communication), CW1103+254 (Beuermann, Stella and Krautter 1984) and AM Her itself (Heise et al. 1984), have been measured using EXOSAT.

3.1.1 Light Curve Compendium. Figures 1 and 2 illustrate the LE (0.04-2.0 keV) and, when available, the ME (1-10 keV) light curves of E2003+225, AN UMa, E1405-451, EF Eri, VV Pup and CW1103+254 plotted as a function of optical linear polarisation phase. These data have been taken from the original references (above) and scaled so as to facilitate comparison. The measurements of E2003+225 and VV Pup were made during a single orbital cycle; for the other stars data from more than one orbital cycle have been folded together. Recall that the LE and ME instruments sample different spectral components (Section 2.3); i.e. emission from the heated surface of the white dwarf at the polar cap, and bremmstrahlung emission from the shock-heated gas in the accretion column, respectively.

The X-ray light curves of these six stars are clearly of two types. E2003+225, AN UMa, E1405-451 and EF Eri (Figure 1) have a complex low-energy modulation, while emission in the medium energy band is detected from E1405-451 and EF Eri at all phases and has a quasi-sinusoidal orbital variation. The light curves of CW1103+254 and VV Pup (Figure 2) are quite different: For over half of the binary cycle essentially no flux is detected (although a small residual count is observed from VV Pup with the LE detector). Both sources 'turn on' at about phase 0.6, and have an asymmetric light curve with a gradual rise and a more rapid fall. The medium energy emission of CW1103+254 is in phase with the low energy X-ray light curve.

The two extremes of X-ray light curve represented by Figures 1 and 2 can be understood in terms of the orientation of the emitting region compared to the line of sight. In the case of E2003+225, AN UMa, E1405-451 and EF Eri, the 'active' magnetic pole on the surface of the white dwarf lies in the rotational hemisphere that is inclined towards us. Thus for at least part of the orbital/rotation cycle, we see the X-ray emitting region through the accretion column and its immediate environs. The complex light curves of these four stars can then be understood qualitatively in terms of variations in the opacity of the accretion column with viewing angle, coupled with the changing aspect of the X-ray emitting 'hot-spot'. In CW1103+254 and VV Pup, however, the 'active' pole is in the rotational hemisphere of the white dwarf that is inclined away from us. For much of the cycle, the active pole is blocked from view by the body of the white dwarf; we detect flux only when the pole comes over the limb of the star and the light curve is



<u>Figure 1:</u> Orbital/rotational light curves for the Polars E2003+225 (LE), AN UMa (LE), E1405-451 (LE and ME), and EF Eri (LE and ME) plotted as a function of linear polarization phase. The data are repeated twice for clarity. The orbital period of the system is noted above each LE plot. References for these data are given in the text.

comparatively simple because we never view the pole at an acute angle to the accretion column.

A common feature of the low-energy light curves of all the four stars in Figure 1 is a sharp dip in the X-ray flux lasting about 0.1 of a cycle. In the case of AN UMa and E1405-451, the main dip is followed after just over 0.1 in phase by a second, narrower dip. The similarity of the main dip in the four systems is remarkable. It occurs at very similar orbital phases in E2003+225 (ϕ=0.30), AN UMa (ϕ=0.24) and E1405-451 (ϕ=0.27), but slightly later in EF Eri (ϕ=0.42). A similar, but slightly longer, dip is also sometimes seen in the low-energy light curve of AM Her (Tuohy et al. 1978; Section 3.1.2) but centered at about phase 0.07. The dip coincides approximately with the maximum of the medium energy emission in E1405-451 and EF Eri. Patterson, Williams and Hiltner (1981) observed the dip in the light curve of EF Eri using the Imaging Proportional Counter (IPC) detector on the Einstein satellite. They reported that the depth of the dip in EF Eri was energy dependent, and was most prominent at the lowest energies. Since the EXOSAT CMA has no intrinsic energy resolution, this property cannot be confirmed in E2003+225, AN UMa and E1405-451.

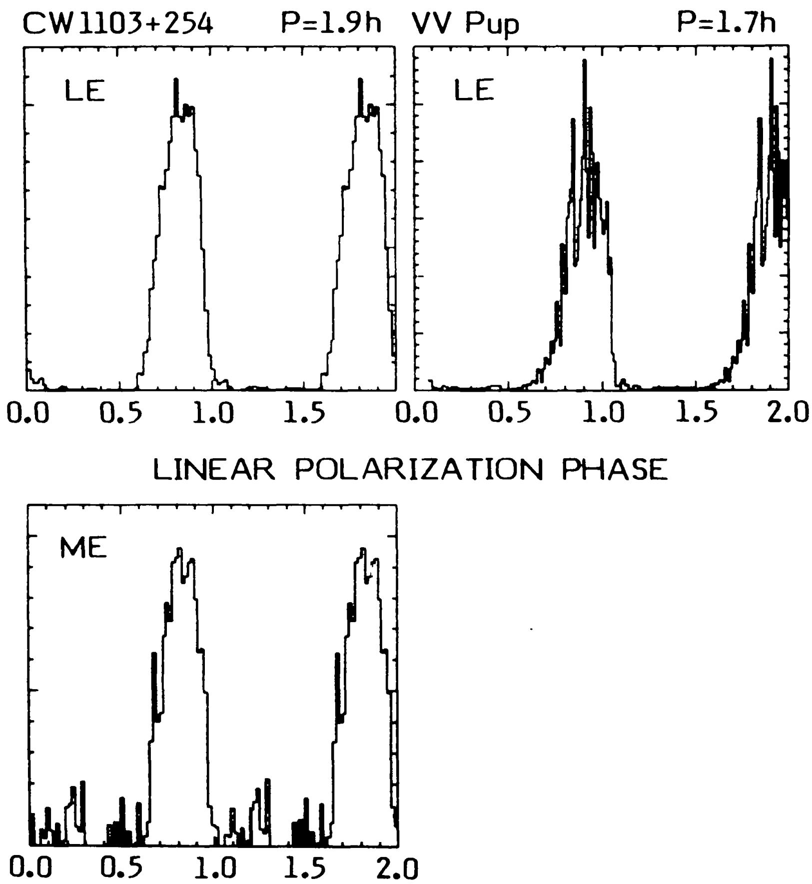


Figure 2: As Figure 1 for CW1103+254 (LE and ME) and VV Pup (LE).

Two explanations that have been put forward for dips such as these is that they are occultations of the emitting pole either by the white dwarf itself or by the accretion column (see for example Patterson, Williams and Hiltner 1981; Osborne et al. 1984a; and references therein). However, the similar phase duration of the dip in all four sources in Figure 1 places a strain on any geometric interpretation of the phenomenon, since it implies that the orientation of the four systems (i.e. their inclination, and the angle between the rotation axis and the magnetic polar axis of the white dwarf) is essentially the same. This is very unlikely unless there is a strong and unknown selection effect operating.

3.1.2 Anomalous State of AM Her. Another surprising result on AM Her variables to emerge from observations with EXOSAT concerns the prototype object itself. AM Her was the first object to be recognised as a polar and is certainly the best studied. The phase averaged soft X-ray light curve of this star was measured, for example, in 1977 with the HEAO-1 satellite (Tuohy et al 1978) and showed a well defined eclipse lasting about 15% of the cycle which started at about the time of the linear polarisation pulse detected in the optical band. The medium energy data also exhibited an eclipse at this time. However, when AM Her was observed between June and September 1983 and again in July 1984, by Heise and his co-workers using EXOSAT, they found the light curve to have changed completely. Whereas previously there had been a soft X-ray eclipse beginning at the phase of the linear polarisation maximum, now the same phase in the cycle corresponded to the middle of a bright state. A much longer "eclipse" or faint state, lasting for just over half the cycle, was now centered at phase ~0.55. The flux in the faint state did not fall to zero, however, but remained at about 10% of the 'bright state' level. In the medium energy X-ray band, the 'eclipses', which lasted for about 20% of the cycle, still coincided with the time of the optical linear polarisation spike (phase 0.0), so that the hard and soft X-ray light curves were out of phase. However, the eclipses of the medium energy flux were now partial, involving only about 50% of the flux.

This anomalous behaviour of AM Her almost certainly signifies a drastic change in the accretion geometry of the source. Perhaps a different magnetic pole, or even more than one pole was emitting. The fact that the medium energy eclipse persisted at the same phase as previously, but was 'filled in' by extra emission favours the latter suggestion.

3.2 Romars (Non-Synchronously Rotating Magnetic Systems)

A property of these systems is coherent pulsations whose "clock" mechanism is ultimately the rotation period of the magnetised white dwarf. As indicated in Section 2.2, the dominant pulsation period detected in the optical band is often the beat between the rotation of the white dwarf and the orbital period of the system. X-ray observations are thus almost always essential in distinguishing the true underlying rotation period of the white dwarf. Observations with EXOSAT have made a substantial contribution in this area, and I discuss a number of individual cases below.

3.2.1 V1223 Sgr. Optical observations of V1223 Sgr had revealed a 13.2 minute optical pulsation (Steiner et al. 1981) together with a transient 14.1 minute periodicity (Warner and Cropper 1984), these being separated in frequency by a value corresponding to the 3.5 hour orbital period of the binary. It was originally though that the 13.2 minute period might be the true rotation period of the white dwarf, but observations with EXOSAT (Osborne et al. 1984b) showed that the 2-10 keV X-ray flux was modulated with a period of 12.43±0.07 minutes. The 13.2 minute period is thus the orbital side-lobe of the white dwarf rotation period of 12.43 minutes. The mean 12.43 minute light curve of V1223 Sgr in the 1.4-8.0 keV band is essentially sinusoidal, with a pulse fraction of 15%. The amplitude of the modulation is a function of energy, however, the pulse fraction being about 13% in the 4-8 keV band and about 18% in the 1.4-4 keV band. It will become apparent that such energy dependence is a common property of the X-ray pulsation in Romars.

3.2.2 H2215-086. In contrast to V1223 Sgr, the dominant optical periodicity of 20.9 minutes found in H2215-086 (Patterson and Steiner 1983) is indeed the rotation period of the white dwarf. Observations with EXOSAT by Cook, Watson and McHardy (1984) and by Osborne et al. (1984b) show the X-ray flux to be modulated at high amplitude with the 20.9 minute period. A low level optical periodicity at 22.8 minutes is the orbital side-lobe of the rotation period. In common with the X-ray modulation of V 1223 Sgr, the 20.9 minute X-ray periodicity of H2215-086 is most pronounced at the lowest energies, the pulse fraction being ~70% between 2 and 5 keV, and ~25% between 5 and 10 keV.

3.2.3 H2252-035 Detailed observations of H2252-035, one of the best studied of the Romars, have been made using EXOSAT by Pietsch et al. (1984). In this system the white dwarf rotates with a period of 805 seconds, a periodicity which is also detected in the optical flux. The dominant optical periodicity is, though, the orbital side-lobe at 859 seconds. Pietsch et al. obtained optical photometry of H2252-035 simultaneous with the X-ray data on two nights, 1983 September 14/15 and 1983 September 17. The 805 second X-ray pulsation and the 859 second optical pulsation were stable throughout the observations, but a 180 degree phase shift was noted in the optical analogue of the 805 second modulation between the two nights. The X-ray and optical modulations were in phase on September 17 and out of phase on September 15. Pietsch et al. also detected the orbital modulation of 3.59 hours in the X-ray flux for the first time. They noted a ~50% reduction in the X-ray emission that lasted for about 20% of the orbital cycle, roughly coincident with the optical orbital minimum. This feature may not be stable in phase either, however, for there is again an indication of a phase shift between the two nights.

3.2.4 TV Col. Observations with EXOSAT have resulted in the first detections of short timescale periodicities in some stars, establishing their membership in the Romar class. Such a case is TV Col which has been found by Schrijver et al. (1985) to have an X-ray pulsation with a period of 1943 seconds at an amplitude of 20%. Motch (1984) has recently reported that the 1943 second periodicity is also detected in optical photometry of TV Col. This system is complex, previous optical observations having established three longer periodicities; 0.22869 days (from optical spectroscopy), 0.2186 days (from optical photometry), and 4.024 days (the beat period of these two).

3.2.5 GK Per One of the earliest and most spectacular demonstrations of the abilities of EXOSAT came from the observation of the ex-nova GK Per. This system has in recent times been undergoing dwarf nova like outbursts approximately every year. During a previous outburst, a relatively strong (for a cataclysmic variable) hard X-ray flux was detected from its vicinity (King et al. 1979). Another optical outburst was detected from the star during the "performance verification" phase of the EXOSAT mission, and the inherent flexibility of the spacecraft as an observatory made it possible to re-schedule a planned observation of GK Per to take advantage of the opportunity presented. This resulted in the discovery of strong, coherent X-ray pulsations with a period of 351 seconds (Watson, King and Osborne 1984), establishing the accreting star in this nova system to be a magnetic white dwarf. Figure 3 shows a section of the ME data on GK Per taken on 1983 August 9. The X-ray pulse profile has a quasi-sinusoidal shape

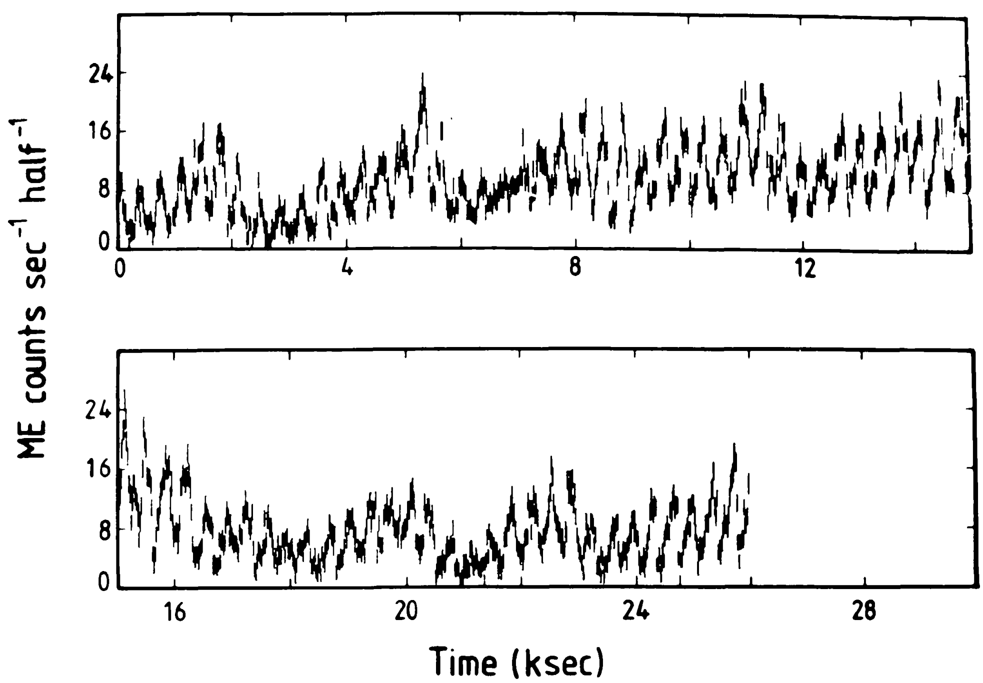


Figure 3: EXOSAT ME data on GK Per taken on 1983 August 9 during an optical outburst. The 351 s oscillations are clearly seen superposed on longer timescale irregular variability. From Watson, King and Osborne 1984.

with a mean amplitude of about 50% above 3 keV, but about 80% between 1 and 3 keV. The amplitude of the pulse is remarkably constant with time, despite irregular changes in the mean flux level on a timescale of 3000 seconds. The X-ray spectrum of GK Per is complex, requiring at least three components to fit both the medium energy and low energy data. GK Per is a particularly interesting cataclysmic system in that its orbital period is atypically long (probably about 2 days) which implies that the secondary is evolved. The mean X-ray flux is indeed consistent with accretion being driven by the nuclear evolution of the secondary. No variation in the X-ray pulse period with orbital phase is detected in the EXOSAT data, but the upper limit is consistent with the expected mass ratio of the system, $M_{WD}/M_C > 3$.

3.2.6 EX Hya. A star that has puzzled optical observers for a number of years is EX Hya. It is an eclipsing system, which fixes the orbital period at 98 minutes; but the optical light also undergoes a large amplitude modulation with a period of 67 minutes. An extended observation of the source was made with EXOSAT on 1983 July 30/31, during the performance verification phase of the mission. The low energy data (0.04-2.0 keV) have been analysed by Cordova, Mason and Kahn (1984), while the medium energy data have been examined by Beuermann and Osborne (1984). The data confirm earlier results from the Einstein satellite (Kruszewski et al. 1981) in showing that the X-ray flux of EX Hya is also strongly modulated with the 67 minute period. Figure 4 illustrates the data from the low-energy (CMA) detector (0.04-2.0 keV), along with data in two energy bands from the ME detector (1-4 keV and 4-9 keV), folded on the 67 minute period using the quadratic ephemeris of Gilliland (1982). Also shown are B band optical data taken in 1983 March and folded using the same ephemeris (Cordova, Mason and Kahn 1984). The mean amplitude of the 67 minute modulation in the 0.04-2.0 keV band is 30%, decreasing to ~10% in the 4-9 keV band. In comparison, the pulse fraction of the 67 minute modulation in the optical band is about 15%. The high amplitude of the X-ray modulation, coupled with the energy dependence characteristic of the Romars, strongly suggests that we are dealing once again with a magnetised white dwarf and that 67 minutes is its rotation period. EX Hya is thus the only Romar so far identified with an orbital period below the well-known gap in the CV orbital period distribution between 2 and 3 hours. It is also the Romar whose white dwarf most nearly co-rotates with the orbital motion.

The EXOSAT data, being a long, continuous timeseries, provide the first opportunity to examine the 98 minute orbital light curve of EX Hya in the X-ray band. Data from the low energy (0.04-2.0 keV) and ME (1-9 keV) detectors are folded using the orbital ephemeris of Gilliland (1982) in the right hand portion of Figure 4.

The 0.04-2.0 keV data folded on the 98 minute period exhibit a broad dip lasting about 1/3 of the cycle and with an amplitude approximately half that of the 67 minute modulation in the same band. The center of the broad dip preceeds the time of optical eclipse by about 75°, and it is interpreted as being caused by absorption in material associated with the mass transfer stream from the companion star. The broad dip is not seen above 2 keV confirming that it is caused by photoelectric absorption, a strongly energy dependent effect. The column density of cold, cosmic abundance material required to produce the observed reduction in flux is about 2 x 10^{19} H atoms cm^{-2}.

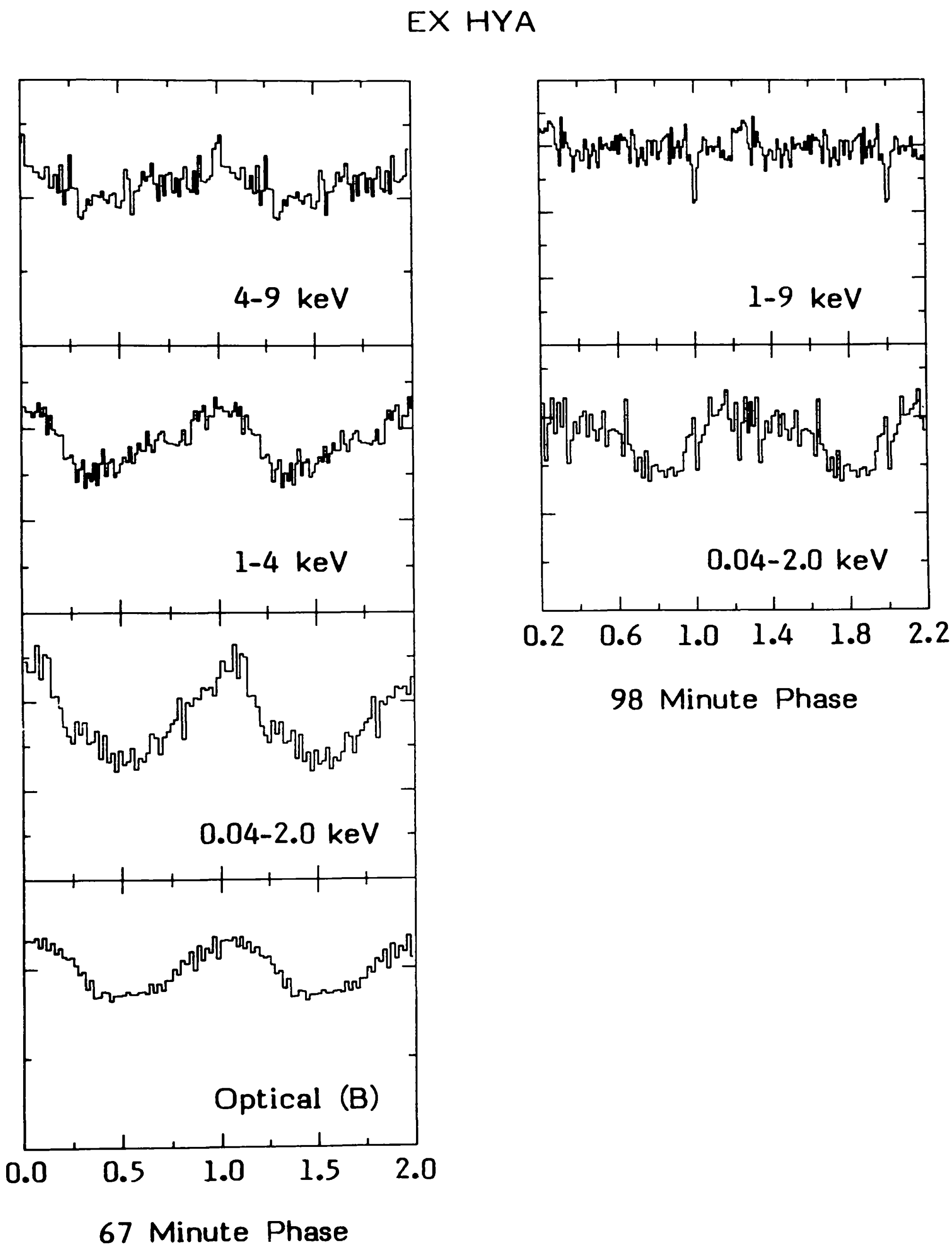


Figure 4: Data on EX Hya folded on the 67 minute period (left column) and the 98 minute orbital period (right column). The ephemerides used are those of Gilliland (1982). The optical data are from Cordova, Mason and Kahn (1984) and were taken in 1983 March. The EXOSAT low energy (0.04-2.0 keV) data are taken from the same reference and represent 26 hours of exposure in various filters. The EXOSAT medium energy data (1-9 keV) are from Beuermann and Osborne (1984) and represent about 16 hours exposure on source. The EXOSAT observation was made in 1983 July.

An important question is whether there is an analogue of the narrow (2-3 minute duration) optical eclipse in the X-ray band. Indeed there is a dip of the right duration in both the LE and ME data at exactly the phase of optical eclipse (defined as phase 0.0 in Figure 4); but the X-ray eclipse is partial, involving only about 25% of the flux. This suggests that the X-ray emitting region is large compared to the size of the white dwarf and that the orbital inclination of the binary is such that the red dwarf companion obscures only part of the X-ray source at mid-eclipse. It is expected that material accreting onto a white dwarf will form a shock above the surface at a height in the accretion column that allows it to cool in the time it takes to free-fall onto the star (e.g. Kylafis and Lamb 1982). The densities likely to be encountered in the accretion column of EX Hya (accretion rate $\sim 10^{16}$ g s^{-1}) are low, so that bremsstrahlung cooling will be relatively inefficient. Thus, provided the magnetic field is weak enough for cyclotron cooling to be unimportant, the stand-off shock in EX Hya may be many white dwarf radii above the surface, and there will be an extended subsonic 'atmosphere' of cooling gas above the star. Even so, since the binding energy of the accreting gas increases as 1/r, much of the accretion luminosity will be emitted close to the stellar surface. Indeed the modulated X-ray source must of necessity be located fairly close to the white dwarf. The observed energy dependance of the 67 minute pulse fraction in EX Hya (and indeed in other Romars) suggests that the innermost emission regions have the lowest spectral temperature.

A final note concerning EX Hya: A periodicity at 46.4 minutes has been distinguished in the optical photometry by Cordova, Mason and Kahn (1984). This is clearly resolved from half the orbital period (49.13 minutes). It is interesting that the ratio between the 46.4 minute period and half the orbital period of EX Hya (0.944) is very similar to the ratio of the 0.2186 day photometric and 0.22869 day spectroscopic periods of TV Col (0.956; Section 3.2.4). It may be that a common mechanism drives the shorter period in both systems, but that mechanism has yet to be identified.

3.3 Weak Field (Disk Accreting) Systems

3.3.1 <u>SS Cyg.</u> The dwarf nova SS Cyg is one of the brightest disk accreting CV in the X-ray band. SS Cyg was observed for 7.5 hours on 1983 December 4 by King, Watson and Heise (1984) using the Medium energy and Low energy detectors on EXOSAT. The star was in its quiescent (inter-outburst) optical state. Flares were seen in the X-ray flux on timescales from tens to hundreds of seconds. The overall range of variability was about a factor of 5 and 10 respectively in the ME (2-20 keV) and LE (0.04-2.0 keV) bands, with individual flaring events on any given timescale involving a change in flux of up to a factor of two. A positive correlation was found between the flux level and the spectral temperature of the emission. The data are consistent with the relationship $Lx \propto T^{1.5+2\epsilon}$ predicted by King and Shaviv (1984) for a radiatively cooling corona surrounding the white dwarf (where ϵ is a small positive number). King, Watson and Heise find that the corona in SS Cyg must cover between 10% and 100% of the surface of the white dwarf. A further datum is that there is a mean delay of about 60 seconds between the flares in the medium energy (2-20 keV) and low energy (0.04-2.0 keV) bands as revealed by a cross-correlation analysis. This is of the same order as the expected cooling timescale of the corona. King, Watson and Heise explain the delay as marking the point where the cooling atoms regain their K-shell electrons and the gas becomes optically thick to its own radiation. This causes a second peak in the flux of low energy X-rays.

3.3.2 VW Hyi One of the stiking features of the dwarf novae SS Cyg and U Gem is intense ultra-soft X-ray emission during their optical outburst (high accretion rate) state (eg. Cordova and Mason 1983). This emission is pulsed, but the pulsation is not coherent. Instead it can be described mathematically as a random walk in phase (Cordova et al. 1980a; 1984). Similar unstable pulsations have been identified in the optical light of a large number of dwarf novae during outburst.

Prior to the EXOSAT observations, SS Cyg and U Gem were the only dwarf novae from which ultra-soft X-ray emission had been detected, although weak hard X-ray emission is a common feature of these stars in all outburst states (Cordova and Mason 1984). Van der Woerd, Heise and Paerels (1984) have now added a third example, VW Hyi. VW Hyi was observed with EXOSAT on a number of occasions during a superoutburst in November 1983. The soft X-ray and optical light curves of VW Hyi, illustrating the evolution of the superoutburst, are shown in the upper part of Figure 5. The first EXOSAT observation was made 79 hours after the onset of the optical outburst. Between this observation and the second, 12.7 hours later, the source brightened by a factor of ten in the CMA, suggesting that there might be a delay of about 2.5 days between the onset of optical brightening and that in the X-ray band. Such a delay is consistent with the expected transport time of material through the disk. The soft X-ray flux of VW Hyi subsequently declined between about 10 and 14 days into the optical outburst, whereas the end of the optical decline phase did not occur until a few days later.

The case of VW Hyi demonstrates the importance of the extended low energy sensitivity of the EXOSAT CMA compared to previous detectors. For example the low energy proportional counter detectors on HEAO-1 scanned VW Hyi for a total of 30 days, through a superoutburst, normal outburst and quiescent phase, with no detection of soft X-rays (Cordova et al. 1980b). Thus the emission of VW Hyi must have a temperature such that it is not visible above the 0.12 keV threshold of the HEAO-1 detectors, but is visible to the EXOSAT CMA whose passband extends a factor of ~3 lower in energy.

As in the case of SS Cyg and U Gem, the soft X-ray flux of VW Hyi was found to be strongly pulsed; unlike the former stars, however, the pulsation in VW Hyi, which has a period of 14.07 seconds, was coherent to the limits of detectability ($Q>10^7$). A further revealing fact is that the pulsation was only detected at the lowest energies sampled. Although the EXOSAT CMA has little intrinsic energy resolution, a series of filters can be interposed in the light path to give broadband colours. The "thin Lexan" filter, which has its peak transmission between 100 and 200 A, and the Aluminium/Paralene filter, whose sensitivity extends beyond the He II edge at 228 A, were used to observe VW Hyi. Remarkably, the 14 s pulsation was detected only in the Aluminium/Paralene data, suggesting that the pulsed radiation might consist of HeII continuum emission. The lower portion of Figure 5 shows the power spectrum of VW Hyi data taken in the Aluminium/Paralene filter

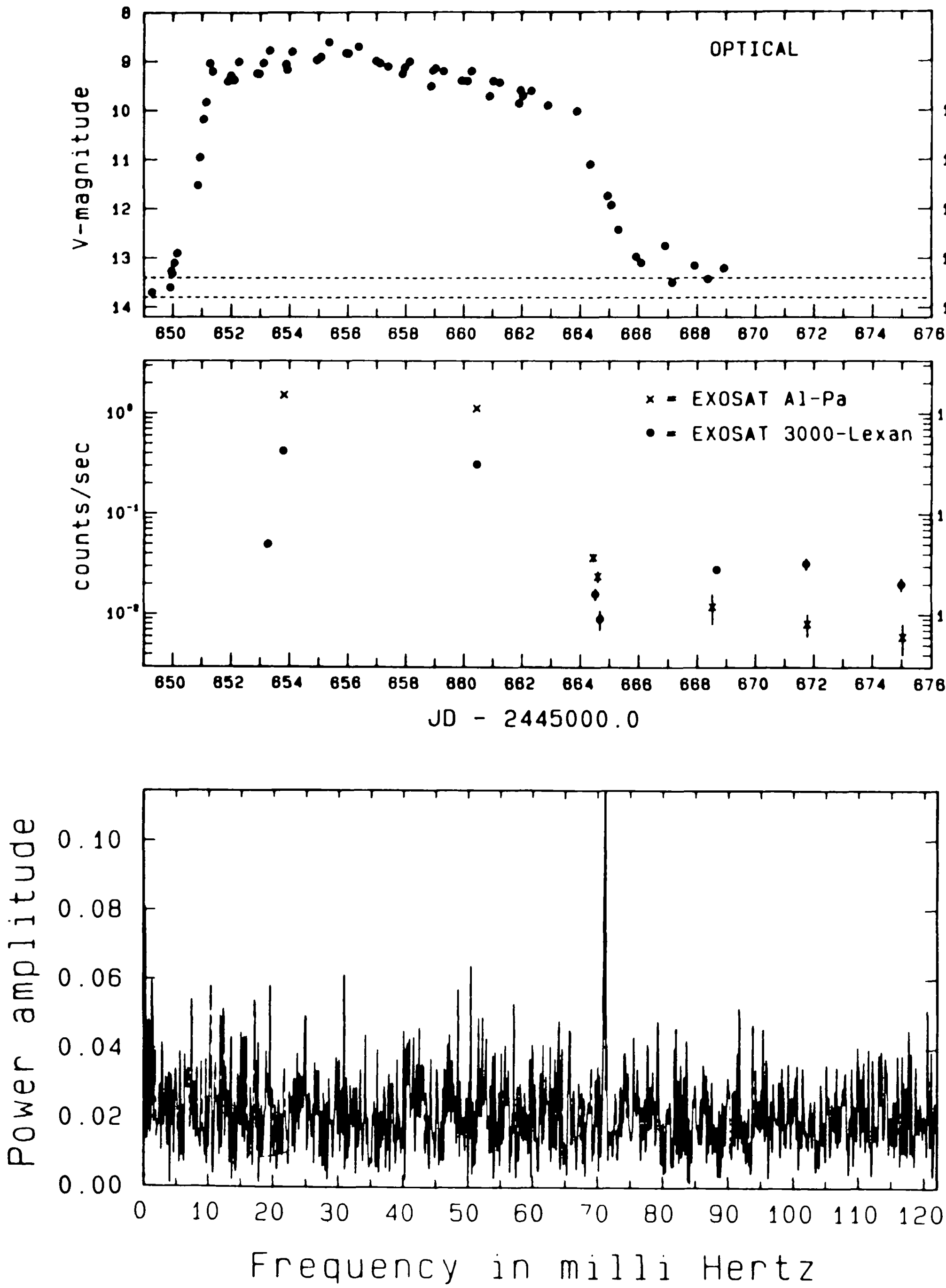


Figure 5: Top two panels: Visual and soft X-ray outburst light curve of VW Hyi. The EXOSAT low-energy X-ray data are taken in two filters; Aluminium Paralene (crosses) and thin Lexan (circles). Bottom panel: Power spectrum of VW Hyi data taken in the Aluminium Paralene filter on J.D. 2445660.

on J.D. 2,445,660, illustrating the narrow spike at 71 milli Hz (14.07 seconds). The mean pulse fraction of the modulation is about 20%.

The high coherence of the pulsations in VW Hyi suggests that the white dwarf in this system might be magnetic, and that the 14 second pulsation is the rotation period of the compact star. If this is true, then VW Hyi possesses the fastest rotating white dwarf known so far; indeed it must be rotating at near break-up speed. King (1984) has pointed out that even very weak magnetic fields can control the transport of energy into the white dwarf surface by electron conduction. Thus, while the magnetic field in VW Hyi may be too weak to disrupt the accretion disk, it might nevertheless give rise to a soft X-ray emitting hot-spot on the white dwarf's surface. A similar model may account for the quasi-coherent soft X-ray pulsations detected in SS Cyg and U Gem, except that the magnetic field must be a transient, surface phenomenon in these stars, not coupled to the core of the white dwarf. A possible mechanism for generating such fields is dynamo action caused by differential rotation in the surface layers of the white dwarf. These fields remain stable for a few rotation cycles, then collapse and re-form at a different longitude. The result is a series of discreet pulse trains, each with the same period, but unrelated in phase. Such a model provides an appropriate mathematical discription of the data on SS Cyg and U Gem (Cordova et al. 1984). It is interesting that an analogous process occurs on the Sun with the formation of active regions. Indeed frequency spectra of solar wind velocity data taken over several years are very similar to those obtained from the soft X-ray outburst data on SS Cyg and U Gem (cf. Figure 2 of Fenimore et al. 1978 and figures in Cordova et al. 1984).

4. CONCLUSIONS

In its first year of operation EXOSAT has already made a substantial contribution to the study of X-ray emission from cataclysmic variables. High quality data have been obtained of a number of Polar systems. These reveal a remarkable uniformity in the morphology of their orbital/rotation light curves. In particular, a narrow dip is seen in the light curve of all the systems observed so far in which the active pole is located in the rotational hemisphere facing us. The fact that the dip is so similar in duration in all the systems is an embarassment to any geometric interpretation of the phenomenon. The inadequacy of our present knowledge of these systems is underlined by the complex changes in beam pattern that have been observed in AM Her. It is likely that this behaviour is related to changes in emphasis between the emission of different magnetic poles of the star, but a detailed understanding is lacking.

Considerable progress has been made in the study of Romars (asynchronously rotating magnetic stars). The X-ray light curves of a number of these have been measured for the first time, and new examples of the phenomenon have been discovered. The X-ray rotational light curves of the Romars as a class are much less complex than those of the Polars. This is consistent with the idea that the X-ray emitting hot spot covers a larger fraction of the stellar surface in the Romars than it does in the Polars. This in turn must be related to the presence of an accretion disk in the former systems which allows accreting material access to magnetic field lines with a wider range of magnetic latitude than in the Polars. It is universally true among the Romars which have been measured that the X-ray pulsation is most pronounced at the lowest energies. This may be because there is an extended atmosphere of hot gas surrounding the white dwarf in these systems.

Observations of the disc accreting variable SS Cyg during its quiescent state verify that hard X-rays are produced in a corona surrounding the white dwarf. The extended low energy response of the EXOSAT detectors has resulted in the discovery of pulsed, ultra-soft, X-ray flux from VW Hyi, only the third example of the detection such emission from a dwarf nova. The high coherence of the pulsations in VW Hyi suggests that weak magnetic fields can be important even in the disk accreting systems.

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REFERENCES

Beuermann, K. and Osborne J. 1984 Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.

Beuermann, K., Stella, L., and Krautter, J. 1984 Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.

Cook, M.C., Watson, M.G. and McHardy, I.M. 1984 M.N.R.A.S. 210, 7P.

Cordova, F.A., and Mason, K.O. 1983 in Accretion driven stellar X-ray sources ed. W.H.G. Lewin and E.P.J. van den Heuvel, Cambridge University Press, Cambridge, England, pg.147.

Cordova, F.A., and Mason, K.O. 1984 M.N.R.A.S. 206, 879.

Cordova, F. A., Chester, T. J., Tuohy, I. R., and Garmire, G. P. 1980a, Ap. J., 235, 163.

Cordova, F.A., Nugent, J.J., Klein, S.R., and Garmire, G.P. 1980b, M.N.R.A.S., 190, 87.

Cordova, F.A., Chester, T.J., Mason, K.O, Kahn, S.M., and Garmire, G. P., 1984 Ap. J., 278, 739.

Cordova, F.A., Mason, K.O. and Kahn, S.M. 1984 M.N.R.A.S. (in press).

Fenimore, E.E., Asbridge, J.R., Bame, S.J., Feldman, W.C., and Gosling, J.T. 1978 J. Geophys. Res., 83, 4353.

Gilliland, R.L., 1982 Ap. J. 258, 576.

Heise et al. 1984 (in preparation).

King, A.R. 1984 Nature (in press).

King, A.R., and Shaviv, G. 1984 Nature 308, 519.

King, A.R.,Ricketts, M.J. and Warwick, R.S. 1979, M.N.R.A.S., 187, 77P.

King, A.R., Watson, M.G., and Heise, J. 1984 Nature (in press).

Kruszewski, A., Mewe, R., Heise, J., Chlebowski, T., Van Dijk, W., and Bakker, R., 1981, Space Sciences Reviews, 30, 221.

Kylafis, N. D., and Lamb, D. Q. 1982 Ap. J. Suppl. 48, 239.
Motch, C. 1984 Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.
Osborne, J., Maraschi, L., Beuermann, K., Bonnet-Bidaud, J.M., Charles, P.A., Chiapetti, L., Motch, C., Mouchet, M., Tanzi, E.G., Treves, A., and Mason, K.O. 1984a Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.
Osborne, J., Mason, K.O., Bonnet-Bidaud, J.M., Beuermann, K., and Rosen, S.R. 1984b Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.
Patterson, J. and Steiner, J.E. 1983 Ap. J. 264, L61.
Patterson, J., Williams, G. and Hiltner, W.A. 1981 Ap. J. 245, 618.
Pietsch, W., Pakull, M., Tjemkes, S., Voges, W., Kendziorra, E., and van Paradijs, J., 1984 Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.
Pringle, J. E., and Savonije, G. J. 1979, M.N.R.A.S., 187, 777.
Schrijver, J., Brinkman, A. C., van der Woerd, H., Watson, M.G., King, A.R., van Paradijs, J., van der Klis, M. 1985 (these proceedings).
Steiner et al. 1981 Ap. J. 249, L21.
Tuohy, I.R., Lamb, K.K., Garmire, G.P. and Mason, K.O. 1978 Ap. J. 226, L17.
Tylenda, R. 1981, Acta Astr., 31, 127.
Van der Woerd, H., Heise, J. and Paerels, F. 1984 Proceedings of Symposium 'X-ray Astronomy '84', held in Bologna, Italy June 1984, ed. Y. Tanaka.
Warner, B. and Cropper, M. 1984 Ap. J. 206, 261.
Watson, M., King, A.R., and Osborne, J. 1984 M.N.R.A.S. (in press).