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A NEW SOFT X-RAY MODE IN THE AM HERCULIS OBJECT E2003+225[1]

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ABSTRACT

EXOSAT observations of the AM Her object E2003+225 made in 1985 June and September are presented together with optical and ultraviolet observations. The average soft X-ray count rate doubled between 1983 October and 1985 June; the simultaneously measured V band intensity fell by a factor of 3 and the UV flux by 20%. The medium-energy X-ray flux did not increase significantly. In 1985 September E2003+225 was observed to have a radically different soft X-ray light curve to that seen previously, but an average intensity similar to that of 1985 June. The new soft X-ray light curve showed two similar peaks and two unequal minima separated by half a period. The optical light curve observed 2 days earlier showed no major change in shape. These observations provide a serious challenge to the standard model of AM Her objects.

Subject headings: X-rays: binaries — X-rays: sources

I. INTRODUCTION

E2003+225 was discovered to be an AM Her object by Nousek *et al.* (1984) who report on *HEAO 1* and *Einstein* X-ray observations together with optical spectroscopy, photometry, and polarimetry. These authors derived a geometry which has the accreting pole visible for almost the entire orbital period of 3.71 hr, the longest of all the known AM Her objects.

In a previous paper (Osborne *et al.* 1986, hereafter Paper I), we described simultaneous X-ray, UV, and optical spectroscopy and photometry of E2003+225 obtained in 1983 October. The soft X-ray light curve was found to be complex, similar to those of AN UMa and E1405−451 (Osborne *et al.* 1984), which are thought to have a similar geometry. The temperature of the soft X-ray blackbody component was measured with the *EXOSAT* 500 lines mm^{-1} grating to be in the range 18–29 eV ($T = 2.1$–3.4×10^5 K). This allowed a comparison of the luminosities of the various spectral components and showed that the blackbody luminosity was greater than that of the thermal bremsstrahlung component, but of the same order as the optical-UV luminosity.

Phase resolved studies of the complex optical emission line spectra have been described by Mukai *et al.* (1986, hereafter Paper II) who reported changes in the intensity, light curve, and line velocities of the optical emission. Mukai and Charles (1986) have detected the secondary star and derive a lower limit to the distance of 215 pc.

In this *Letter* we report quasi-simultaneous X-ray ultraviolet, and optical photometric and polarimetric observations made at two epochs in 1985 (see Table 1). These observations show remarkable changes with respect to those of 1983 and 1984 described in Papers I and II. Long-term changes in soft X-ray and optical-UV brightness are anticorrelated and the shape of the soft X-ray light curve changed radically between the two 1985 observations.

Throughout this *Letter* we use the ephemeris provided by Cropper (1986), which is derived from cross-correlation of the optical light curve over 4 yr. It reads: T_{max} = HJD 2,445,234.8364(4) + 0.15452105(6)E; the error in the last digit is shown in brackets. Phase zero refers to the time of the linear polarization pulse. This ephemeris is more precise than that of Paper I. The phases of events in Papers I and II are not significantly affected by the adoption of the new ephemeris.

II. OBSERVATIONS

a) *X-Rays*

EXOSAT observed E2003+225 on 1985 June 10 and September 14 for more than four orbital periods on each occasion (see Table 1). The observations were made almost entirely with the 3000 Lexan filter (0.06–1.9 keV) in the low-energy telescope (LE1). The Al/P filter (0.04–0.08, 0.13–1.8 keV) was inserted briefly at the end of each observation. The Medium Energy (ME) instrument (1–10 keV) was used in its offset mode, the on-source and off-source instrument halves being swapped every 3.5 hr. The instruments are described by de Korte *et al.* (1981) and Turner, Smith, and Zimmermann (1981).

i) *Light Curve*

In 1985 June the orbit-averaged soft X-ray intensity measured with the 3000 Lexan filter was 0.969 ± 0.005

[1] Based on observations taken with the *EXOSAT* and *IUE* satellites and at Calar Alto and La Palma. The Calar Alto Observatory is operated by the MPI für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy. The Jakobus Kapteyn Telescope is operated on the island of La Palma by the Royal Greenwich Observatory as part of the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canaries.

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TABLE 1

OBSERVATION LOG

Epoch	Observatory	Day of Month	Time
1985 Jun	*EXOSAT* CMA + 3Lex	10/11	1451–0616
	EXOSAT CMA + Al/P	11	0620–0639
	EXOSAT ME	10/11	1429–0651
	IUE	10/11	2155–0447
	Calar Alto (2.2 m)	11	0024–0234
1985 Sep	*EXOSAT* CMA + 3Lex	14/15	2134–1307
	EXOSAT CMA + Al/P	15	1311–1349
	EXOSAT ME	14/15	2113–1312
	IUE	17	1512–1758
	La Palma (1.0 m)	12/13	2225–0210

counts s^{-1}, a factor of 2.0 times higher than in 1983. In 1985 September this intensity was 1.186 ± 0.006 counts s^{-1}. The folded soft X-ray light curves, plotted against linear polarization phase, are shown in Figure 1 (*left*). It is immediately obvious that the form of the soft X-ray light curve has changed radically between the two 1985 observations, although their average intensity differs only by $\sim 20\%$.

The 1985 September soft X-ray light curve shows two similar maxima and two minima: one minimum (at $\phi = 0.43$) being total, the other (at $\phi = 0.93$) reaching 8% of the peak count rate. The small step at $\phi = 0.51$ corresponds exactly in phase and has a similar width to a narrow dip in the earlier light curve. In contrast, the total minimum in 1985 September occurs $0.1 P_{\rm orb}$ later than in the earlier observations, suggesting a different physical origin for the total minimum and the feature at $\phi = 0.51$.

Another difference between the two soft X-ray light curves is their variability on a time scale of minutes. The September light curve exhibits large-amplitude ($\sim 50\%$ modulation) pulses with recurrence times of 4–11 minutes. Pulse trains longer than three pulses are not seen. The June data show no such pulsations. The short time scale variability will be analyzed in a future publication (Osborne 1987).

ii) *X-Ray Spectrum*

In 1985 the grating was not available for spectral measurements in the soft X-ray band. However, some constraints can be derived from the ratio of count rates in different filters. The 1985 September light curves exhibit large variations on short time scales and are too variable to yield meaningful spectral estimates, but the 1985 June data show no variations $> 9\%$ in the time intervals of interest. In 1985 June the Al/P data refer to the phase interval $\phi = 0.86$–0.95. Using the count rates accumulated in the four corresponding phase intervals of the 3000 Lexan observation we obtain a ratio (3000 Lexan:Al/P) $R = 7.2 \pm 0.8$, where the error is the quadratic addition of the statistical error and an allowance of 9% for variability. We fix the column density, $N_{\rm H}$, at 10^{20} $\rm cm^{-2}$, which is the maximum allowed value derived from the grating observation of 1983, as suggested by the distance and interstellar column density estimates (Mukai and Charles 1986; Paresce 1984). These values of $N_{\rm H}$ and R translate into an admissible blackbody temperature range of 18–25 eV. With this allowed temperature range the observed doubling of the soft X-ray count rate corresponds to a bolometric luminosity variation by a factor of between 2.2 and 0.6. For the lower values of $N_{\rm H}$ allowed in 1983 the implied variation factor is larger than 0.6.

E2003+225 was barely detected by the ME detectors in 1983; the average channel 9–24 count rate was 0.15 counts s^{-1} in four detectors. This corresponds to a 2–6 keV flux of 1.5×10^{-12} ergs $\rm cm^{-2}$ s^{-1} for a thermal bremsstrahlung spectrum with $kT > 1$ keV and no absorption. In 1985 June and September the hard X-ray source was not seen. The 2 σ upper limits to the channel 9–24 count rate are 0.31 counts s^{-1} in eight detectors and 0.17 counts s^{-1} in seven detectors, respectively, corresponding to flux limits of 1.58×10^{-12} and 1.02×10^{-12} ergs $\rm cm^{-2}$ s^{-1} over 2–6 keV. Thus this spectral component has not significantly increased its brightness over the level seen in 1983.

b) *Ultraviolet*

E2003+225 was observed by *IUE* on 1985 June 10 and September 17 (see Table 1). On June 10 six exposures in each wavelength range (SW 1200–2000 Å and LW 2000–3000 Å) were obtained covering nearly two orbital cycles. On September 17 nearly one orbital cycle was covered with four exposures (two SW, two LW). The light curves, obtained by fitting the data in each wavelength range separately with power-law spectra and computing the 1950 Å flux from these fits, are shown in Figure 1 (*center*).

A comparison of the 1950 Å light curves obtained in 1984 July (Paper II) and 1985 June and September shows the following:

1. 1984 July and 1985 June appear broadly similar although the average intensity in the later data is $\sim 20\%$ lower. The orbital peak is less broad and less prominent; the off-peak flux is the same in the two light curves.
2. The 1985 September data show an intensity slightly lower still. The maximum seen around $\phi \approx 0.7$ on both previous occasions is not visible in this light curve, although coverage is incomplete.

c) *Optical*

Multicolor photometry was obtained by K. B. in 1985 June using the 2.2 telescope at Calar Alto. A folded V band light curve taken simultaneously with the *EXOSAT* observation (see Table 1) is shown in Figure 1 (*right*). These are the first simultaneous high-resolution photometric and soft X-ray observations of E2003+225. The average magnitude was $V \approx 15.3$, typical for this object (Andronov and Yavorskii 1983). The source was exceptionally bright ($V \approx 13.8$) at the time of the simultaneous optical and X-ray observations of 1983 October.

White-light circular and linear polarization observations were made on June 11/12 and June 12/13, respectively, 1 and 2 days after the X-ray observations. The times of the two linear polarization pulses observed are consistent with the ephemeris of Cropper (1986) used in this *Letter*. The phase dependence of the circular polarization was very similar to that of Nousek *et al.* (1984).

CCD photometry of E2003+225 was carried out in 1985 September from La Palma as a service observation by Dr. P. Jorden (see Table 1). The 1.0 m Jakobus Kapteyn Telescope, equipped with the GEC CCD camera at the f/15 Cassegrain focus, was used with V, R, and I filters. A dichroic mirror

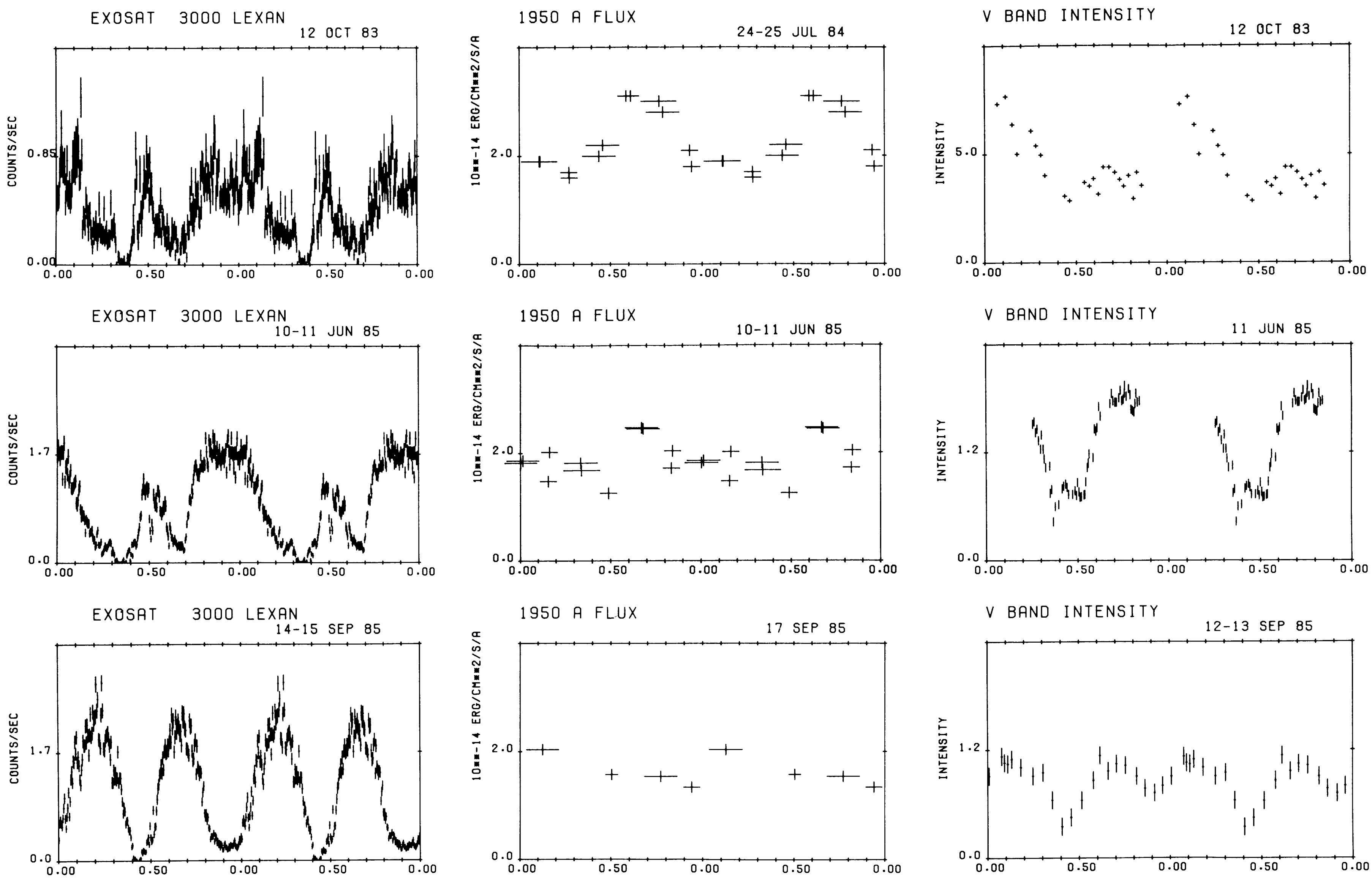

FIG. 1.—The *EXOSAT* 3000 Lexan soft X-ray light curves from 1983 October (Paper I) and 1985 June and September folded over the orbital period and plotted twice against linear polarisation phase. The 1983 observation was $1.0P_{\rm orb}$ in length; both 1985 observations were longer than $4P_{\rm orb}$. Note the different intensity scale for the 1983 data. (*center*) The intensity at 1950 Å derived from fits to short- and long-wavelength *IUE* spectra folded as in Fig. 1 (*left*). The top panel shows the 1984 June data (Paper II); the lower panels show data taken close to the times of the 1985 *EXOSAT* observations. (*right*) Folded V band intensities normalized such that an intensity of 1.0 corresponds to $m_v = 15.5$. (*top panel*) One orbital period of spectrophotometric data taken simultaneously with the X-ray data in 1983 October (Paper I). (*middle panel*) Photometry covering $0.6P_{\rm orb}$ obtained from Calar Alto simultaneously with the 1985 June *EXOSAT* observation. (*bottom panel*) V band CCD photometry covering $1.0P_{\rm orb}$ obtained from La Palma 2 days prior to the 1985 September *EXOSAT* observation. Note the different intensity scale for the 1983 data.

was inserted in order to use the blue starlight for guiding. This produces an uncertainty of 0.1 mag in the absolute V magnitude, while relative photometry is accurate to 1%. The V light curve is shown in Figure 1 (*right*).

The brightness range in 1985 September was some 0.5 mag fainter than that of the June observation. There is no evidence for any phase shift between the two 1985 optical observations. The flat-bottomed minimum is not evident in the later light curve, which resembles the U band light curves of Nousek *et al.* (1984) and of Paper II.

III. DISCUSSION

Our main findings are the following:

1. Between 1983 October and 1985 June there was a twofold increase of the soft X-ray intensity associated with a comparable decrease of the optical flux, a smaller decrease of the UV flux, and no significant increase in the medium-energy X-ray flux.
2. A dramatic change occurred in 1985 September of the shape of the soft X-ray light curve, without any large variation of the average intensity; the optical light curve at the same epoch did not show major changes, although the visual magnitude faded by 0.5 mag.

a) The Change in the Soft X-Ray Light Curve

As discussed in Paper I the earlier soft X-ray light curve (which we shall call "complex") is difficult to interpret. However, the new light curve (here called "simple") is easier to understand. Interpreting this light curve as due to the changing projected area of the polar cap as the system rotates (see, e.g., Imamura and Durisen 1983), the flatter minimum at $\phi = 0.93$ is due to the closest approach of the polar cap to the limb of the white dwarf, consistent with the appearance near this phase of the linear polarization spike and the geometry of the source derived by Nousek *et al.* (1984). The expected phase of maximum projected area is $\phi = 0.43$; however, at this phase the accretion column is between the polar cap and the observer and can thus screen off the emission from its base. We attribute the total minimum of the soft X-rays at $\phi = 0.43$ to the intervening accretion column. This causes the observed orbit-averaged 0.1–0.25 keV flux to be reduced by 60%.

Let us now discuss the nature of the "complex" mode in which the maximum flux occurs at $\phi \approx 0.9$. A comparison with the behavior of AM Her may be useful. This object was observed over several years to have a soft X-ray light curve with a single peak at $\phi \approx 0.6$ and an eclipse during $\phi = 0.0$–0.2, similar to that at higher energies. The X-ray maximum coincided with the primary optical minimum. In 1983 a reversed mode was observed by Heise *et al.* (1985) where the soft X-ray maximum was shifted by $\Delta\phi = 0.5$, while the shape of the optical and medium-energy X-ray light curves remained unchanged (Mazeh, Kieboom, and Heise 1986). We suggest a parallel between the so-called normal mode of AM Her with the "simple" mode of E2003+225, since both can be understood as the emission from a single pole. Note that a similar behavior is also exhibited by E1405−451 which has recently shown a new simple mode very similar to that of E2003+225 (Osborne, Cropper, and Cristiani 1987).

The reversed mode of AM Her was interpreted by Heise *et al.* (1985) as due to a second accreting pole. This may also be the case for the complex mode of emission from E2003+225. However, two difficulties should be mentioned, both of which also apply to AM Her:

1. The existence of a second pole does not show up in the optical light curve.
2. The soft X-ray light curve does not appear to be due to two small flat diametrically opposed emission regions. In particular, the pole closest to the red dwarf is the weakest in this light curve, at least in soft X-rays.

Alternatively we can consider the complex light curve to be due to a single pole. We are then forced to postulate a peculiar matter distribution above the polar cap which reprocesses the soft X-rays to give a maximum at $\phi \approx 0.9$. The presence of a second peak at $\phi \approx 0.5$ requires that the matter responsible for reprocessing is inhomogeneous and is semitransparent along the axis (on this point see Paper I).

b) The Optical–X-Ray Anticorrelation

We now come to our other major observational result, namely the opposite sense of variation of the optical and X-ray average intensity. In the standard picture (e.g., Lamb and Masters 1979) the soft X-rays are interpreted as due to reprocessing of the optical cyclotron and the medium-energy X-rays by the body of the white dwarf. In E2003+225 the optical luminosity was shown to be comparable to the soft X-ray luminosity in 1983 October (Paper I), whereas the medium-energy X-rays provided a minor contribution. The observed opposite variation of the optical and soft X-ray fluxes strongly conflicts with this scheme. We note that Priedhorsky, Marshall, and Hearn (1986) have reported a similar lack of correlation of the optical, soft, and hard X-ray fluxes from AM Her.

The tight relationship between the hard X-ray, optical, and soft X-ray luminosities in the Lamb and Masters model can be relaxed if direct heating of the polar cap by the kinetic energy of high-density filaments in the accreting flow is allowed (Kuijpers and Pringle 1982).

We conclude that the heating and reprocessing mechanisms which operate near the accreting pole(s) of AM Her objects are more complex than suggested in the simplest models and hope that these observations stimulate interest in more detailed theoretical work.

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