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THE DISCOVERY OF THE 2 HOUR MODULATED X-RAY SOURCE EXO 033319−2554.2, AN AM HERCULIS SYSTEM

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ABSTRACT

We report the discovery of EXO 033319−2554.2, a soft X-ray source with 100% modulation of its soft X-ray flux, found during a systematic analysis of all of the *EXOSAT* soft X-ray data. The soft X-ray light curve, which has an on-off behavior, allows us to derive a period of 127.7 ± 3.0 minutes. The bright part of the cycle lasts 0.55 in phase and is cut by an eclipse-like feature lasting 8 minutes, with unresolved ingress and egress, 0.13 in phase after maximum intensity. These features of the soft X-ray light curve were the same in 1983 and 1986. The soft X-ray color requires blackbody temperatures less than 25 eV; the source was not seen by the medium energy instrument. The optical counterpart has a magnitude of $m_v \approx 18.5$.

The characteristics of EXO 033319−2554.2 imply that it is an AM Her system. The companion star is probably responsible for the eclipse, given its shape and position. EXO 033319−2554.2 is probably the second eclipsing AM Her system and, as such, will allow high-quality measurements of the white dwarf synchronicity in the future. Using the lengths of the bright phase and of the eclipse, we derive limits to the system geometry. The soft and hard X-ray data imply that the blackbody luminosity is greater than the hard X-ray luminosity thermalized by the white dwarf.

Subject headings: stars: accretion — stars: individual (EXO 033319−2554.2) — stars: magnetic — stars: white dwarfs — X-rays: binaries — X-rays: sources

I. INTRODUCTION

A common characteristic of AM Herculis binaries is an intense soft X-ray flux, believed to originate from a blackbody-like spectral component of a few tens of eV close to the magnetic pole(s) of the accreting white dwarf. Such systems, when located within 200–300 pc, can easily be detected by the present generation of soft X-ray telescopes, and a number of new AM Her systems have been discovered using X-ray observations (Biermann *et al.* 1985; Morris *et al.* 1987; Remillard *et al.* 1986; Beuermann *et al.* 1987). The Channel Multiplier Arrays (CMA) of the *EXOSAT* telescopes (Taylor *et al.* 1981), with their large field of view (~2 deg^2) and high sensitivity to very soft X-rays (0.05–2.0 keV; de Korte *et al.* 1981), are excellent instruments for discovering new X-ray sources belonging to this class.

In this *Letter* we report the discovery of EXO 033319−2554.2 (Giommi *et al.* 1987), a soft X-ray source modulated at a period of ~128 minutes. The X-ray and optical data presented here imply that EXO 033319−2554.2 is an AM Her system. Beuermann and Thomas (1987) have shown that the optical counterpart has a period consistent with that seen in X-rays.

II. OBSERVATIONS

The high galactic latitude field including EXO 033319−2554.2 was observed with *EXOSAT* in 1983 August and in 1986 January. On both occasions a serendipitous source was detected in the CMA ~ 34′ off-axis. The celestial positions from the two observations agree within 10″ and have a mean of $\alpha_{1950} = 03^h33^m19\overset{s}{.}9$ and $\delta_{1950} = -25°54'14''$. The estimated 90% confidence position error radius is 20″. Consistent with this position there is only one candidate optical counterpart in the Palomar Observatory sky survey plates (see Fig. 1 [Pl. L2]). Later optical observations by Beuermann and Thomas (1987) showed that this object has a period of 126.5 minutes, consistent with that of the X-ray source and that it then had the spectrum of an AM Her system in a low state.

During the first observation the CMAs of both low-energy X-ray telescopes (LE1 and LE2) were operational and the source was observed simultaneously with filters having different spectral transparencies. LE1 was operated with the aluminium/parylene (Al/P) and boron filters, and LE2 with the 3000 Å Lexan (3LX), polypropylene (PPL) and 4000 Å Lexan filters (4LX). The source was not detected when the boron filter was in use. The source light curve in the two telescopes is given in Figure 2 (*upper panels*), which shows that the source exhibited a well-defined on-off behavior. The time difference between the points where the source changed from "off" to "on" in the PPL data is 7860 s, with an uncertainty of about 4 minutes.

The modulation was clearly periodic in the second observation. Approximately three cycles were seen with the Al/P filter and one bright phase with the 3LX filter. These data were folded over a range of trial periods and fit to a constant. The maximum value of χ^2 corresponded to a period of 7635 s. An alternative technique, fitting the phase of each cycle from the second observation with a template obtained from the first, gave a period of 7660 s with a 1 σ error of 180 s. This is consistent with our other results, and we have adopted this value in what follows.

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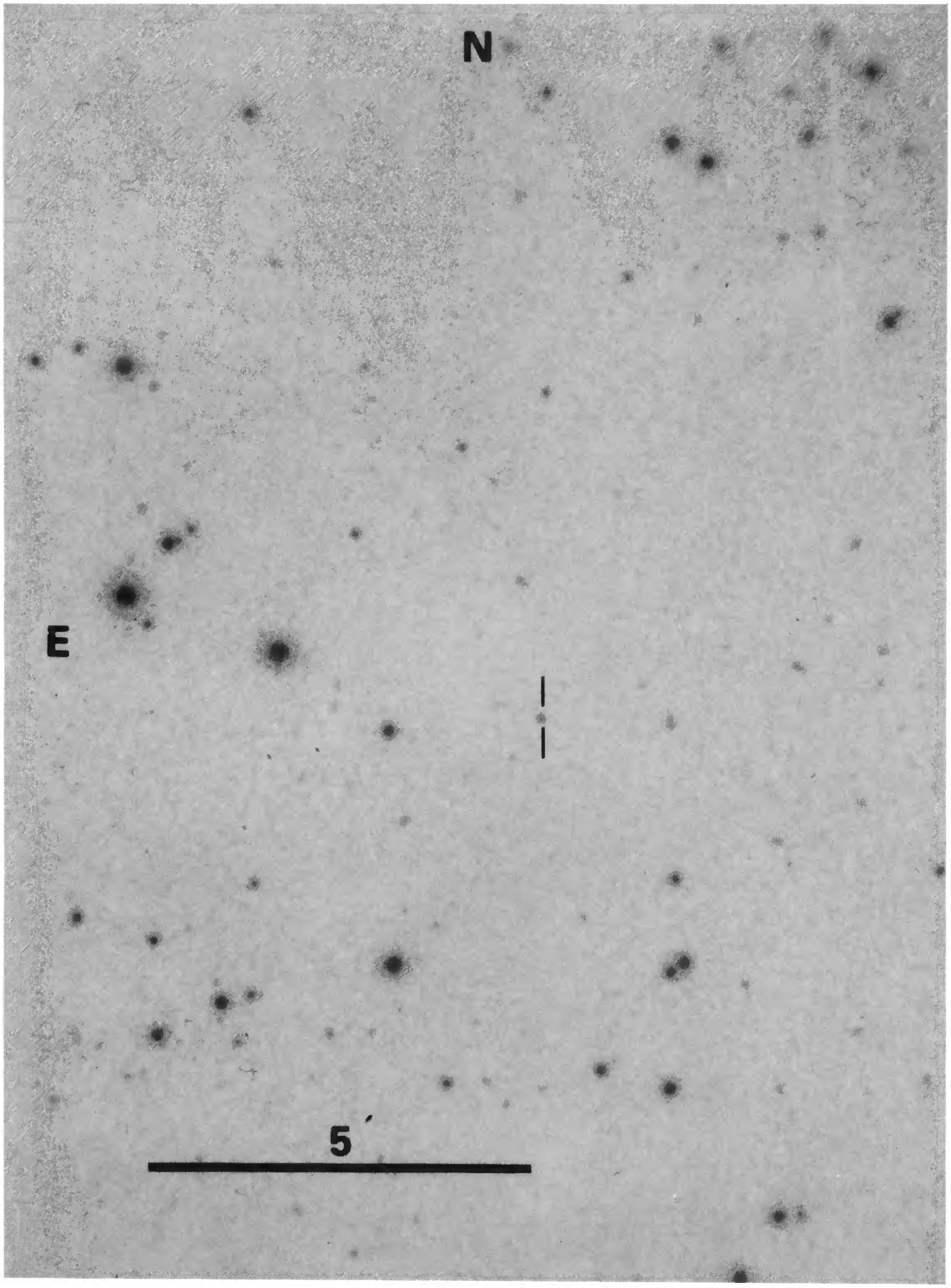

FIG. 1.—The Palomar Sky Survey E (red) plate showing the only object within the 90% confidence region for the position of EXO 033319−2554.2 derived from the *EXOSAT* data. North is up, and east is on the left. The star marked has $m_B \approx m_V \approx 18.5$ and is at $\alpha_{1950} = 03^h33^m20^s.89$, $\delta_{1950} = -25°54'17''.4 \pm 0''.5$ (Burg and McLean 1987).

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The light curves from the two observations were folded over the ~128 minute period for the various filters separately (see Fig. 2). An eclipse-like feature with a width of 8.0 ± 0.5 minutes is clearly seen in the light curves ~0.13 in phase after the center of the bright phase. The source is not detected during this interval (see Table 1). The edges of this feature are not resolved at a bin width of 20 s. The central times of this feature during the PPL (1983) and 3XL (1986) observations were HJD 2,445,567.17697 ± 0.00016 and HJD 2,446,446.97317 ± 0.00016, respectively. These epochs define phase zero in Figure 2 and throughout this *Letter*.

In addition to the 128 minute modulation, the light curve showed variability on timescales of a few minutes. This was more pronounced during the 1986 observation, when count rate changes of up to 100% were observed. The most dramatic of these fluctuations caused the count rate in the 3LX filter to

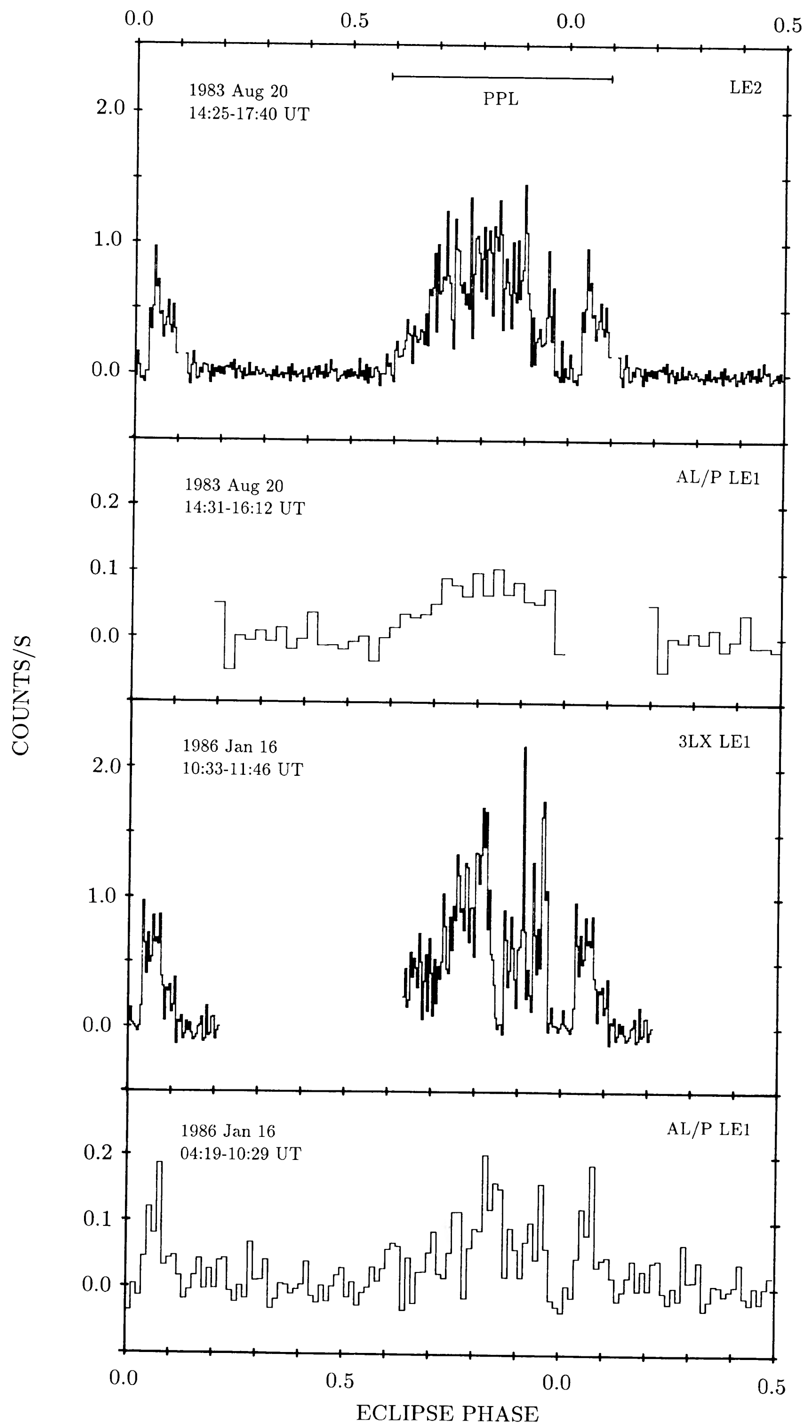

FIG. 2.—The *EXOSAT* low-energy X-ray light curves of EXO 033319−2554.2 folded on a period of 7660 s (1.5 periods shown). The center of the eclipse defines phase zero. In the top panel the bright phase is mostly seen through the PPL filter; the 3000 Å and 4000 Å Lexan filters (which have a similar transmission curve to PPL) were used before and after this. The top three panels do not contain significantly more than one cycle of data; the bottom panel contains three cycles. The on-off behavior of the source is clearly seen. These soft X-ray light curves are very similar to those seen from the AM Her systems E1114+182 and VV Pup.

TABLE 1

EXOSAT LOW-ENERGY TELESCOPE COUNT RATES

Date of Observation	Filter; Telescope	Bright Phase (0.65–0.95)	Faint Phase (0.20–0.55)	Eclipse (0.97–0.03)
1983 Aug 20......	PPL; LE2	0.71 ± 0.03	...	<0.09
	3LX; LE2	...	<0.020	...
	4LX; LE2	...	<0.024	...
	Al/P; LE1	0.062 ± 0.011	<0.018	...
1986 Jan 16.......	3LX; LE1	0.65 ± 0.02	...	<0.06
	Al/P; LE1	0.072 ± 0.007	<0.015	<0.03

NOTE.—Count rates are counts s^{-1} and are corrected for vignetting and other effects (Osborne 1985). Upper limits are 3 σ. Quoted errors are 1 σ and represent statistical uncertainties. Estimated systematic errors are 10% and are due to uncertainties in the CMA calibration at large off-axis angles (see Giommi and Angelini 1987).

decrease to <0.13 counts s^{-1} (3 σ upper limit) for 150 s at phase 0.855, near the expected time of the maximum. The mean count rate in adjacent intervals of the same width was 0.74 ± 0.07 counts s^{-1}. A similar feature was not observed at the same phase in the folded Al/P light curve from the three preceding cycles; the source was detected here at 0.12 ± 0.03 counts s^{-1}.

We fitted the folded light curves of Figure 2 (excluding the 1983 Al/P data) with a function of the form $f(\phi) = a + b \cos [2\pi(\phi + \phi_0)]$ if f positive, $f(\phi) = 0$ otherwise (where ϕ is the phase) which represents the variation of the projected area of an infinitesimal spot on the surface of a sphere as it rotates. We excluded intervals obviously affected by flickering and the eclipse [$\phi = 0.90 - 1.05$ in 1983, $\phi = 0.82 - 1.05$ (3LX) and $\phi = 0.88 - 1.05$ (Al/P) in 1986]. Acceptable fits, giving consistent allowed parameter ranges, were obtained with each data set. We derived the length of the bright phase, $\Delta\phi = \cos^{-1}(-a/b)/\pi$, and the delay between maximum intensity and the eclipse center, ϕ_0, from the weighted means of the best-fit parameters. Our results are $\Delta\phi = 0.550 \pm 0.015$ and $\phi_0 = 0.133 \pm 0.006$ (90% confidence). Integration of our best-fit curves over the intervals labeled "bright phase" in Table 1 yields expected count rates 5% greater than those given, except for the 1986 3LX data where a 57% larger count rate is obtained.

Blackbody spectra were convolved with the response of the low-energy telescopes and compared with the bright phase count rates determined simultaneously from the PPL and Al/P observations in 1983 (see Table 1). The 1986 observation was not used because the observations with the two filters were not simultaneous. The 90% and 99% confidence limits on the temperature, kT_{bb}, and the bolometric blackbody luminosity, L_{bb}, are shown in Figure 3. The blackbody luminosity is normalized as $L_{bb} = \pi f_{bb,bol} d_{100}^2 / \langle \cos(\psi) \rangle$, where $f_{bb,bol}$ is the bolometric blackbody flux (integrated here over phases 0.65–0.95), d_{100}^2 is the distance in units of 100 pc, ψ is the time-dependent

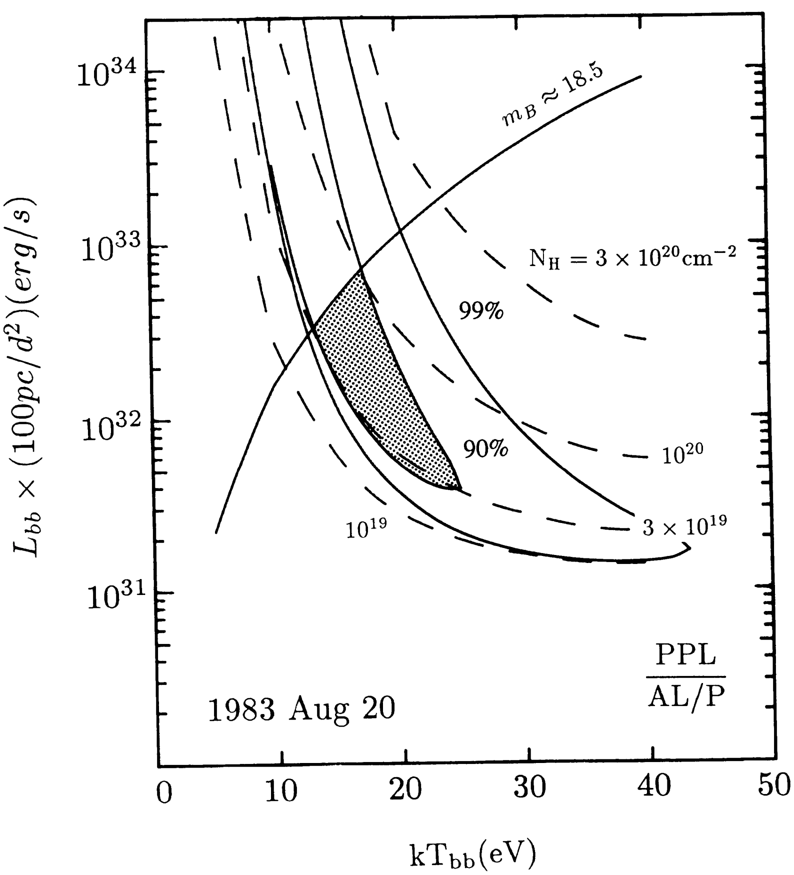

FIG. 3.—The 90% and 99% confidence limits of the bolometric blackbody luminosity, L_{bb}, and blackbody temperature, kT_{bb}, derived from the simultaneous PPL and Al/P filter observations in 1983. Lines of constant equivalent hydrogen column density are shown dashed. We assume that the luminosity is the minimum physically possible within the limits of the allowed geometry (see Fig. 4). The line labeled $m_B \approx 18.5$ represents an upper limit to L_{bb} assuming that the blackbody spectrum is responsible for all of the B-band flux. We note that $m_B \approx 18.5$ may correspond to a different intensity state to the X-ray data.

angle between the line of sight to the emission region and the normal to the white dwarf surface there, and $\langle\cos(\psi)\rangle$ is the average of $\cos(\psi)$ over the phase range used to determine $f_{bb,bol}$. The value used for $\langle\cos(\psi)\rangle$ in Figure 3 (0.78) corresponds to the lowest luminosity possible given the limits to the geometry (see discussion and Fig. 4).

The maximum blackbody temperature allowed by this observation is 25 eV; the minimum luminosity is $4 \times 10^{31} d_{100}^2$ ergs s^{-1} (all limits correspond to 90% confidence). The equivalent hydrogen column density, N_H, is limited to $> 2.5 \times 10^{19}$ cm^{-2} and is probably less than 1.3×10^{20} cm^{-2}. We note that the neutral hydrogen column density through the galaxy in the direction of EXO 033319−2554.2 is 1.0×10^{20} cm^2 (Stark *et al.* 1988).

The source was included at ~30% efficiency in the collimator response of the Medium Energy experiment (ME; Turner, Smith, and Zimmermann 1981). No evidence for a source flux in the 1–6 keV range was found, with 90% confidence upper limits (after correction for the collimator) of 1.0 counts s^{-1} and 0.5 counts s^{-1}, respectively, for the first and second observations over the bright phase. These limits refer to four ME argon detectors. The 1983 limit corresponds to an observed flux limit of $f_{1-6} < 1.3 \times 10^{-11}$ ergs cm^{-2} s^{-1} assuming a thermal bremsstrahlung spectrum with a temperature of 50 keV. The upper limit to the total luminosity, $2\pi f_{tot} d_{100}^2$, of a hard X-ray component is $4.4 \times 10^{31} d_{100}^2$ ergs s^{-1}. This limit includes an allowance of 5% uncertainty in the area of the ME detectors. The upper limit for a 10 keV spectrum is 43% of that for a 50 keV spectrum. We conclude that a hard X-ray component could not have contributed more than 0.097, 0.082, and 0.040 counts s^{-1}, respectively, in the 3LX, PPL and Al/P filters.

III. DISCUSSION

There is strong evidence that EXO 033319−2554.2 is an AM Her system:

1. No other class of astronomical objects with a 100% modulated periodic soft X-ray light curve is known that would not also be a hard X-ray source easily detectable by *EXOSAT* given the observed soft X-ray intensity.
2. The soft X-ray light curve of EXO 033319−2554.2 is strongly reminiscent of those from AM Her systems where bright phases of comparable duration to faint phases are generated by the polar cap rotating behind the white dwarf limb (e.g., VV Pup, Patterson *et al.* 1984; E1114+182, Biermann *et al.* 1985).
3. The ~128 minute period of the modulation is within the range of orbital periods of AM Her–type systems.
4. The soft X-ray color indicates a very soft spectrum, similar to most other AM Her binaries.

This identification supported by an observation of the optical spectrum, which is like that of an AM Her system in a low state (Beuermann and Thomas 1987).

Some preliminary conclusions about the system geometry can be obtained from the soft X-ray light curves. In the approximation of a pointlike emission region, the duration of the bright phase $\Delta\phi$ is related to the system inclination i and the colatitude of the accreting spot δ by $\cos(\pi\Delta\phi) = -\cot\delta\cot i$. From Figure 2 we have derived $\Delta\phi = (0.550 \pm 0.015)$; the corresponding constraints on the values of i and δ are plotted in

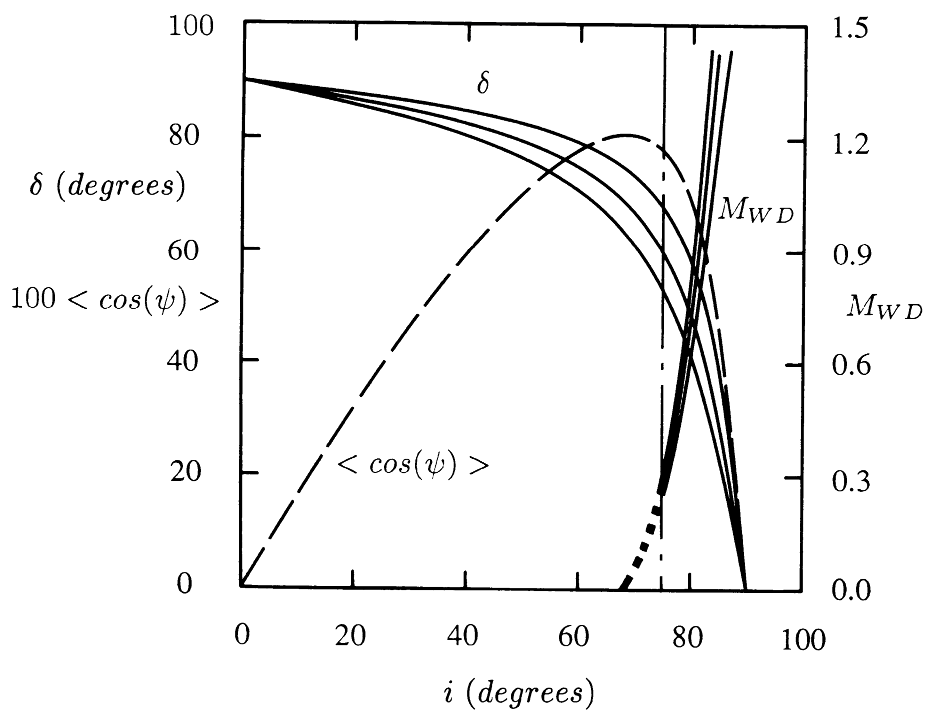

FIG. 4.—The colatitude of the emission region, δ, as a function of system inclination, i, derived from our estimate of the duration of the bright phase, $\Delta\phi$; the 90% confidence limits are also shown. The dashed curve, labeled $\langle\cos(\psi)\rangle$, gives the geometric correction factor (see text). The curves labeled M_{WD} give the implied white dwarf mass as a function of inclination under the assumption that the eclipse is due to the companion (see text). Again, the best estimate and 90% confidence limits are shown. These curves are shown dotted at mass values for which conservative mass transfer is not possible (Rappaport, Joss, and Webbink 1982). Using this argument, the lower limit to the inclination is 75°, shown as a dot-dashed line. The value of $\langle\cos(\psi)\rangle$ corresponding to this inclination was used in the calculation of the blackbody luminosity.

Figure 4. If the emission region were actually extended in azimuth, as has been suggested for the AM Her systems CW 1103+254 (Cropper 1986) and EF Eri (Beuermann, Stella, and Patterson 1987), higher values of δ would be allowed.

The recurrent soft X-ray dip seen $0.13P_{\rm orb}$ after soft X-ray maximum is intriguing. It is narrow ($0.06P_{\rm orb}$), total, and has unresolved ingress and egress. The dip is similar in width both to those seen in EF Eri, E2003+225, AN UMa, and E1405−451 (reviewed by Osborne 1988), which are most probably due to the accretion stream passing through the line of sight (King and Williams 1985), and to the dip seen in E1114+18 which is due to the companion star eclipsing the white dwarf (Biermann *et al.* 1985).

In EXO 033319−2554.2 the unresolved dip ingress and egress suggest that the dip may be due to the companion. The maximum soft X-ray count rate almost certainly corresponds to closest approach of the emission region to face-on; the delay in phase, ϕ_0, to the time of the dip then tells us that the emission region on the white dwarf leads the companion star in azimuth by $48° \pm 2°$. This angle is larger than any seen in a study of five AM Her objects by Mukai and Charles (1987), which included AM Her itself.

If the dip were due to the accretion stream rising out of the orbital plane, then the azimuthal separation of the emission region and the red star must be greater still. This is because the accretion stream is expected to move to earlier phases, due to orbital motion, as it falls from the red star to the magnetic capture point (Liebert and Stockman 1985). We are therefore left with an eclipse by the companion as our best guess for the cause of the recurrent dips seen in EXO 033319−2554.2.

If the eclipse in this object is due to the companion, then, by assuming that the secondary obeys the empirical ZAMS mass-radius relationship of Patterson (1984) and fills its Roche lobe, and by using Kepler's third law, we find that the white dwarf mass is related to the system inclination as shown in Figure 4. Mukai and Charles (1987) have determined that all of the white dwarfs in four well-studied AM Her systems have a mass which lies in the range 0.45–0.75 $M_\odot$, similar to the mass of isolated white dwarfs. If we assume that the mass of the white dwarf in EXO 033319−2554.2 also lies in this range, then from Figure 4 we obtain $i = 77°$–$81°$, $\delta = 65°$–$38°$. This geometry, with $i > \delta$, predicts that the accretion column will pass through the line of sight prior to the eclipse. Flickering is observed at this time, but not the well-developed absorption dips of E2003+225 (Osborne *et al.* 1987) or EF Eri (Beuermann, Stella, and Patterson 1987), suggesting that δ may be larger than, or of the same order as the inclination. Our data allow this if the emission region is extended in azimuth.

We now come to the question of the relative hard and soft X-ray luminosities of this system. The standard model (Lamb and Masters 1979; King and Lasota 1979) predicts that the blackbody luminosity will not be greater than the hard X-ray luminosity if cyclotron emission contributes only a small fraction of the source luminosity. We did not detect hard X-rays. From the 1983 data we derive 90% confidence upper limits to the luminosity of a hard X-ray component of 4.4×10^{31} and 1.9×10^{31} ergs s^{-1} for thermal bremsstrahlung temperatures of 50 and 10 keV, respectively, and a distance of 100 pc (assumed throughout this discussion). The simultaneously determined 90% lower limit to the blackbody luminosity is 4×10^{31} ergs s^{-1}. It thus appears possible that the soft X-rays could be powered by a hard X-ray source.

A number of points must be raised before this conclusion can be accepted, however. The correction factor, $\langle \cos(\psi) \rangle$, might be only one-third of the value used (i.e., $M_{\rm WD} = 1.4\ M_\odot$; see Fig. 4). This would lead to a blackbody luminosity limit approximately 3 times the hard X-ray limit (which is not affected by the mean viewing angle). In addition, the hard X-ray albedo of the white dwarf is expected to be ~ 0.3, and this raises the required observed hard X-ray to blackbody luminosity ratio to ~ 1.8 if the luminosity balance is to hold (King and Watson 1987). Our results do not allow such a ratio. Finally, Williams, King, and Brooker (1987) have shown that blackbody luminosities derived in the way described here lead to underestimates of the luminosity of the illuminated white dwarf atmosphere for reasonable absorbing column densities. From their Figure 7 we estimate that the polar cap atmosphere has a luminosity ~ 70% higher than that derived by us. Thus the polar cap atmosphere luminosity must be at least 3 times the luminosity of the thermalized hard X-rays. We therefore conclude that the white dwarf in this system is either heated by the impact of high-density "blobs" brought to rest below the photosphere (Kuijpers and Pringle 1982) or by cyclotron radiation from the postshock accretion flow.

We thank Richard Burg and Brian McLean for obtaining the precise optical position using the STScI guide star system, and Klaus Beuermann for reminding us about extended emission regions. The members of the *EXOSAT* Observatory team are thanked for their support.

Note added in manuscript.—The identification of EXO 033319−2554.2 as an AM Her system has been confirmed by the detection of cyclotron harmonics in the optical spectra (Beuermann, Thomas, and Schwope 1988; Ferrario *et al.* 1988) and of strong circular polarization modulated at the orbital period when the object was in a high state (Bailey *et al.* 1988). These observations also confirm the presence of deep eclipses with a residual magnitude of $m_v = 20.5$–20.9, suggesting a distance at least a factor of 2 greater than the nominal 100 pc used in this *Letter*.

A recent preprint (Hameury, King, and Lasota 1988) on EXO 033319−2554.2 announces that the current (1988 February, unpublished) version of Ritter's cataclysmic variable catalog shows EXO 033319−2554.2 as having the longest period of all the cataclysmic variables below the period gap.

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