VARIABILITY OF SOFT X-RAY EMISSION OF EX HYDRAE OBSERVED WITH EINSTEIN OBSERVATORY

A. Kruszewski[1,2], R. Mewe[3], J. Heise[3], T. Chlebowski[4],
W. van Dijk[3], R. Bakker[5]

[1]Warsaw University Observatory, Warsaw, Poland
[2]European Southern Observatory, Garching, FRG
[3]Space Research Laboratory, Utrecht, The Netherlands
[4]Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass., USA
[5]Astronomical Institute, University of Amsterdam, Amsterdam, The Netherlands

The cataclysmic variable star EX Hydrae has been observed with the High Resolution Imager (HRI) and the Imaging Proportional Counter (IPC) onboard the Einstein Observatory. The X-ray position is coincident within 3 arcsec of the optical position as measured on Schmidt survey plates. During a 15 1/2 hour observation with IPC we have searched for a modulation of the X-ray flux. Strong evidence for a 67 min period (one of two known optical periods) has been found in the energy range 0.1-3.5 keV with the IPC. The time dependence of modulations is used to discuss a model and evolutionary status of this close binary system.

1. INTRODUCTION

The cataclysmic variable EX Hydrae is known to be a spectroscopic and eclipsing binary (Kraft and Krzeminski, 1962). Its short period of 98.26 min places this object into the ultra short-period subgroup of cataclysmic variables (Patterson, 1979c; Vogt, 1980).

The discovery of an additional periodic variation in the optical brightness of EX Hydrae with a period of 67 minutes which has remainded stable for over ten years (Vogt et al., 1980) has emphasised its unique character.

Various suggestions have been offered concerning the origin of 67 min variations (Vogt et al., 1980; Papaloizou and Pringle, 1980; Sherrington et al., 1980; Breysacher and Vogt, 1980; Cowley et al., 1981; Warner and McGraw, 1981). They include rotation of the white dwarf, disc instability and periodic mass transfer.

EX Hydrae is known to emit during optical quiescence both soft X-rays (0.7-2 keV) (Cordova and Riegler, 1979) and hard X-rays (2-10keV)

Z. Kopal and J. Rahe (eds.), Binary and Multiple Stars as Tracers of Stellar Evolution, 457–466.

(Watson et al., 1978 and references cited herein) at a flux level at Earth of 10^{-10} erg/cm^2/s in each energy interval. The total X-ray flux is of the same order as the optical flux. In fact, EX Hydrae seems to be one of the brightest X-ray sources among all dwarf novae in quiescence. The early X-ray observations did not show any clear evidence for flux variations with either 98 min orbital or additional 67 min period.

In this paper we report the observational results obtained with the high-resolution imager (HRI) and the imaging proportional counter (IPC) onboard the Einstein Observatory.

2. OBSERVATIONS

EX Hya was at first observed for approximately 3.9 hrs (net 1.04 hrs) centered around 10 42 UT on Jan 14 with the HRI onboard Einstein. A detailed description of the instrumentation characteristics can be found in Giacconi et al. (1979).

The high spatial resolution of the HRI permits an accurate position determination within a few arcsec (the 1σ error radius is typically 4."5 (Grindley 1980)). The measured HRI position of EX Hya is: $\alpha(1950)$ = 12 h 49 m 42.4 s and $\delta(1950)$ = -28° 58' 41."4, which is within 3" from the optical position (12 h 49 m 42.41 s ; -28° 58' 38."7).

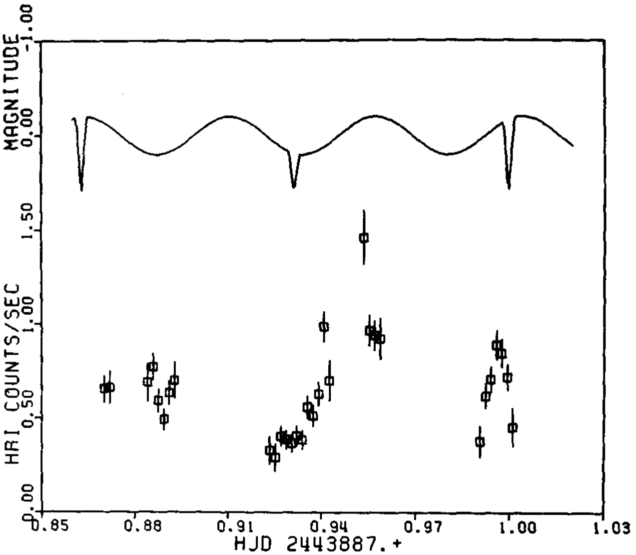

Figure 1. X-ray light curve of EX Hya as measured with HRI onboard Einstein Observatory on January 14, 1979. On top is drawn a highly schematic optical light curve, showing the phase of the periodic variations and the times of eclipses, which repeat every 98 min due to the orbital motion.

The optical position was measured on two Palomar Sky Survey prints and on two ESO Quick Blue Survey glass copies. Its accuracy is about 0."5, and excellent agreement between Palomar and ESO values indicate that annual proper motion of EX Hya is smaller than 0."05/year. The agreement between the optical and X-ray positions confirms very well the previous identification of the X-ray source with its optical candidate (Warner, 1972; Watson et al., 1978; Schwartz et al., 1978).

In the lower half of Figure 1 we present the observed HRI counting rate as a function of time. The counts are binned in 150 s intervals in order to smooth the Poisson noise. For comparison, the upper half represents a schematic optical light curve with eclipse minima, the phase of which was calculated with the epochs and periods from Vogt et al. (1979. Large X-ray variations are visible but the HRI observations

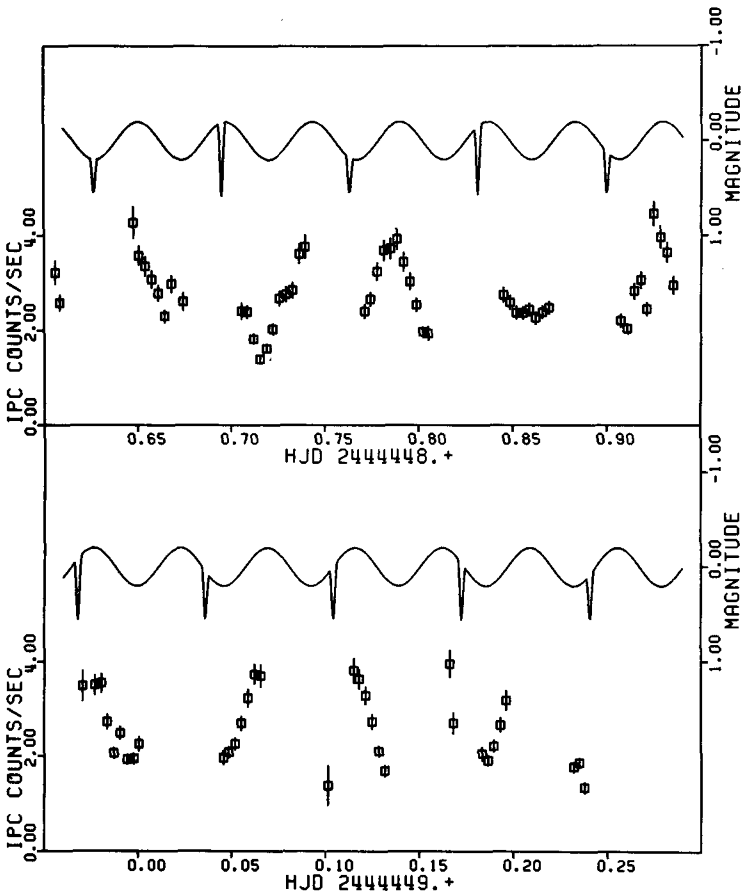

Figure 2. X-ray light curve (0.1-5 keV) in 300 s bin integrations as measured with IPC onboard Einstein Observatory on July 28, 1980. A highly schematic optical light curve is also shown for comparison.

cover a too short time interval for drawing any firm conclusions about relations between the optical and X-ray variations. A new, over 15 hrs long set of Einstein observations was obtained on July 28, 1980. This time the IPC was used as a detector. Figure 2 shows these observations binned in 300 s intervals compared with a schematic optical light curve. The positive correlation between the X-ray and optical modulations is well visible. Fig. 2 leaves no doubts that the 67 min variations are also present in the soft x-ray spectral region.

Unfortunately in the phases around the times of the photometric eclipses, there are gaps due to the South Atlantic Anomaly, so hardly anything can be concluded about the presence of eclipses in the X-ray flux.

Figure 3 presents a power spectrum of the IPC observations calculated with the help of the Deeming (1975) method. The power spectrum of the original uncorrected observations binned in intervals of 100 s is presented in the middle part of Figure 3. In the upper part a spectral window, shifted to have its highest peak at the frequency of the

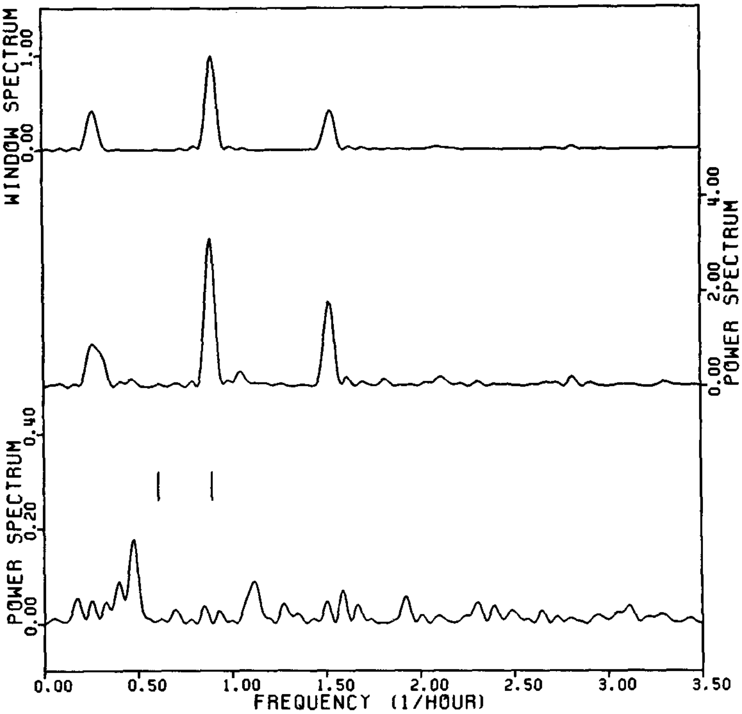

Figure 3. Power density spectrum of the X-ray light curve of Figure 2 (middle) accompanied by the observational data window spectrum (top), and by power density spectrum calculated after the 67 min periodic component has been removed.

67 min variations, is presented. Two sidelobes in the power spectrum correspondes closely to similar sidelobes in the spectral window. The differences in their heights and shapes are most likely due to the superimposed noise. But because of the closenes of the sideral satellite period (94 min), which is reflected in the spectral window, to the orbital period of the binary system (98 min), this difference may also indicate the existence of sidelobe variations in the system. A weak trace of a first harmonic of the fundamental 67 min variations is also present. No signs of higher harmonics and of variations with the orbital frequency can be seen.

The absence of the orbital frequency in the power spectrum speaks nothing about the absence or presence of X-ray eclipses because corresponding phases have not been propely observed, but it indicates instead, that there are no variations between eclipses with the orbital period.

The lower part of the Fig. 3 presents a power spectrum of the IPC signal calculated after the 67 min fundamental and its first harmonic have been removed. The vertical scale has been 10 times enlarged. We see that both sidelobes have been almost completely removed, and that the power spectrum is now dominated by noise. It indicates therefore, that the sidelobes seen in the middle part of this Figure are due to the beating with the satellite siderial period, and that there is no additional periodicity in the object.

3. DISCUSSION

EX Hya is not the only object among cataclysmic binaries which shows an additional coherent periodic variations. It has been known since a long time (Walker, 1956) that an eclipsing post-nova DQ Her shows coherent short-term oscillations with a period of 71 s. Recently three more objects with similar periods have been discovered. They are WZ Sge with a period of 28 s (Robinson et al., 1978), V533 Her with a period of 63 s (Patterson, 1979a) and AE Aqr with a period of 33 s (Patterson, 1979b). These periods are around 3 orders of magnitude shorter than the corresponding orbital periods. On the other hand there exists a class of objects, called AM Her type objects or white dwarf magnetic binaries or polars, where brightness variations are caused by a white dwarf rotating synchronously with the orbital motion (Chiappetti et al, 1980; Stockman et al., 1981). EX Hya was the first object found to be situated between these two extrema with its 98 min orbital period and additional 67 min variations (Vogt et al., 1980). Two more were added recently. The system H2252-035 shows a 215 min orbital period and 14 min optical brightness oscillations (Patterson and Price, 1981). And finally another cataclysmic binary 2A0526-328 is found to have a photometric period only little shorter than the orbital period (Motch, 1981; Hutchings et al., 1981). We are listing here only objects with stable periods and not those, like SU UMa type objects or nova V1500 Cyg, where variations are transient and periods highly variable.

Out of 12 objects with stable optical variations, not caused by orbital motion, 10 are observed as X-ray sources (Chiappetti et al., 1981; Patterson et al., 1980; Schwartz et al., 1979; Patterson and Price, 1981; Patterson, 1981), and 6 out of these (AM Her, AN UMa, 2a0311-227, VV Pup, AR Aqr, EX Hya) show X-ray flux variations with periods equal to the optical periods. In addition, the source H2252-035 shows X-ray flux variations with a frequency that is larger than the optical variations frequency by exactly a single orbital frequency (White and Marshall,1980; Patterson and Garcia, 1980), thus proving that the variable optical flux is caused by X-rays coming from a rotating compact component and reprocessed in an atmosphere of a secondary star. For most of these objects there are good reasons to believe that such periodic variations are caused by rotation of the white dwarf. It is natural then to consider such an explanation also for EX Hya. We shall look now into the background informations about EX Hya in order to infer what these informations tell us about the rotating white dwarf hypothesis.

Broad band photometric data is summarised by Vogt, Krzeminski and Sterken (1980). The observed eclipses have variable depth ranging from 0.3 mag to 0.8 mag and they have also variable width and shape. There is only a small hump observed to appear just before the eclipse (Mumford, 1967) and therefore the "hot spot" can not be very conspicious.

The narrow eclipses and small humps which repeat with the orbital cycle do not dominate the optical light variations of EX Hya. The more conspicious is the 67 min periodic variability together with superimposed fast flickering. Vogt, Krzeminski and Sterken (1980) saw 67 min variations in almost every observational run in a time interval of 14 years. The amplitude is variable, even from cycle to cycle, ranging from 0.05 mag to 0.9 mag, and shows a tendency to increase secularly from 0.2 mag in 1962 to 0.4 mag in 1976. This last statement is contradicted by Quinley et al. (1980) who have not seen 67 min variations in more recent observational material. There are several multicolor observing runs obtained, but up to now very little informations are published on the color dependence of the 67 min variations. In particular, Sherrington et al. (1979) publish in their Fig. 5 the V and K measurements folded with the 67 min period. One can see from that Figure that the amplitude with the K filter (2.2μ) is about twice smaller than with the V filter (0.55μ).

Vogt et al. (1980) say that the 67 min period is stable, what means that there are no difficulties with keeping cycle count and that a linear ephemeris is sufficient to predict nearly all times of maxima with an accuracy better than 10 minutes. The observations reported in this paper give clearly significant deviations from the Vogt et al. (1980) ephemeris, therefore it is interesting to take a closer look at the secular behaviour of the 67 min period. At first it was tried if there is any sign of period variability in Table 4 of Vogt et al. (1980) which contains times of maxima of 67 min variations. The parabolic fit has resulted in the following ephemeris:

$$\mathrm{HJD(maximum)} = \underset{\pm 6}{2437699.8896} + \underset{\pm 36}{0.046546508} \times N - \underset{\pm 3.5}{6.1} \times 10^{-13} \times N^2$$

One can see that there is only a marginal evidence for a decrease of the 67 min period.

Shortly before conducting the IPC observations, the star was observed for a total of 2.9 hrs on July 10, 11, and 12 with the Dutch 90 cm optical telescope equipped with the Walraven photometer at the site of the European Southern Observatory in La Silla, Chile. The visual magnitude of EX Hya varied between 13.4 and 13.9 mag (i.e., the star was in optical quiescence) at the time of these observations. Three maxima of the 67 min period were determined.

We can add new optical timings in order to repeat the parabolic fit on an extended time base. One more time of maximum has been derived from the Fig. 5 of Sherrington et al. (1980). It is HJD=2443986.496 . Because of the way the data was published there is an ambiguity of a few full cycles in the above value. Figure 4 gives all these times of maxima pictured as crosses together with two timings of X-ray observations shown as squares. The parabolic fit with an extended time base, but using only optical data, gives the following result:

$$\mathrm{HJD(maximum)} = \underset{\pm 6}{2437699.8894} + \underset{\pm 25}{0.046546549} \times N - \underset{\pm 2.1}{9.4} \times 10^{-13} \times N^2$$

Now the conclusion about the decrease of the 67 min period is on the 4.5σ significance level and therefore it can be considered as a good

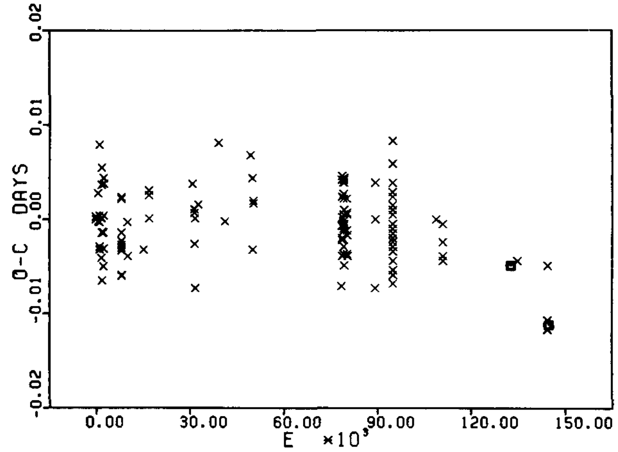

Figure 4. O-C timings of the maxima of the 67 min optical brightness periodic variations (crosses). The last four data points are added to those of Vogt et al. (1980). Also two X-ray timings of the flux maxima are shown (squares).

working hypothesis. The quantity $\dot{P}/P$ is equal -3.17×10^{-7} yr^{-1} and the time scale for the decrease of the 67 min period is 3.1×10^{6} years.

It is interesting to verify if the rotating white dwarf hypothesis is consistent with the derived spin-up rate. Rappaport and Joss (1977) have derived a relevant formula in case of disc accretion on a rotating compact object

$$\dot{P}/P = -3 \times 10^{-5} \times f\ f\ (P/1s) \times (L \times 10^{37} erg/s)^{(6/7)}\ yr^{-1}$$

where P is the period of rotation, L is the luminosity of the compact object due to the accretion, and f is a numerical factor whose value was estimated by Rappaport and Joss as 0.003 in the case of white dwarfs. Accepting P=4022 s and $\dot{P}/P=-3.17 \times 10^{-7} yr^{-1}$ we may solve this equation for L what gives $L=3 \times 10^{33}$ erg/s what in turn is not unreasonable for an object like EX Hya. Therefore we can say that the derived rate of the decrease of period is consistent with the rotating white dwarf hypothesis.

The ultraviolet and optical spectrophotometry (Bath et al., 1980) gives for EX Hya a spectrum which is consistent with that predicted by a steady accretion disc model. The extension of the measured spectrum into the infrared (Sherrington et al., 1980) results in the conclusion that the accretion disc is quite extensive and in particular it extends down nearly to the white dwarf surface. Sherrington et al. even conclude from the derived disc dimensions that the central white dwarf must be of radius smaller than 5×10^{8} cm what in turn implies a large, close to the Chandrasekhar limit, mass (1.4 $M_{\odot}$). This conclusion can be relaxed somehow by taking into account possible contributions to the spectrum from both stellar components, but it seems likely that the white dwarf mass is high and that there is not much free space left around it.

Spectroscopic observations (Kraft, 1962; Breysacher and Vogt, 1980; Cowley et al., 1980) show the presence of wide emission lines which have a double structure and an "S-wave" component. The measurements of the emission line wings resulted in deriving the parameters of the orbital motion of the primary (Breysacher and Vogt, 1980; Cowley et al., 1980). The resulting masses range from 0.7 to 1.5 $M_{\odot}$ for the primary and from 0.16 to 0.19 $M_{\odot}$ for the red secondary component. The observations of Breysacher and Vogt (1980), made in 1976, show a strong dependence of the emission lines intensities on the phase of the 67 min variations. There is some phase-shift present with respect to the used ephemeris. The maximum of the line intensity occurs at phase 0.9 of the 67 min variations in case of the hydrogen and neutral helium lines. The less accurate data for He II 4686 line give the maximum of intensity at phase 0.72 . The observations of Cowley et al. (1980), made in 1980, do not show a clear dependence of emission line intensities on the 67 min phase. Certainly their observations of Hβ do not fit to a cosine curve with a maximum at phase 0.9, but the fit is much better if the phase of maximum is shifted to 0.7. And this can be treated as an independent confirmation of the 67 min period decreasing.

An important observational constraint is the measured total width of the emission lines which gives the rotation speed of the innermost part of the accretion disc to be 3500 km/s (Cowley et al., 1980). Using the Shipman (1977) tabulation of the mass/radius relation for white dwarfs, and assuming high orbital inclination, it is possible to derive a lower limit 0.7 M for the white dwarf mass. In this limiting case the disc extends down to the white dwarf surface. For higher masses there may be some free space between disc and the white dwarf.

The above reasoning are leading us to a tentative conclusion about a rotating white dwarf with a nonuniform surface brightness being a source of optical and X-ray 67 min variations of EX Hya. The greatest difficulty that we have encountered so far is little space that is left to form an accretion column between disc and star surface. There is another difficulty originating from not detecting any linear or circular polarization in the optical spectral range (Krzeminski et al., 1981; Knoechel and Vogt, cited by Breysacher and Vogt, 1980). By analogy with AM Her type objects, one can expect that the variable optical component in EX Hya is polarized. This prediction is not so firm, however. Detailed models of radiation processes in magnetic binaries (Masters et al., 1977; King and Lasota, 1979) give a picture of polarized cyclotron radiation competing with thermal bremstrahlung radiation, with relative roles depending on the accretion rate and the stellar magnetic field strength. For high accretion rates and week magnetic fields the bremstrahlung dominate and no large polarization is expected.

4. EVOLUTIONARY ASPECTS

A decrease in the 67 min period may have an important evolutionary significance. Of course one cannot be sure that the derived time scale of 3 million years really corresponds to a secular evolution of the period. But a rough agreement of this time scale with the expected one for the case of an accreting white dwarf entitle us to consider its consequences for the evolution of its parent binary system.

Extrapolating such a shortening of period back over about 1 million years we obtain equality of both periods. If the white dwarf magnetic field was sufficiently strong at that time, then the white dwarf rotation could be magnetically coupled to the orbital motion. We get therefore a tentative picture of EX Hya being for long time a bright AM Her type object, whose magnetic field got dissipated some one million years ago. The white dwarf lost at that time its hold on a companion star and started to spin up. The derived rate of spin up is not large enough in the present balance of the angular momentum in the system, but ultimately, after many millions of years, an appreciable fraction of the system angular momentum can be stored in the white dwarf rotational motion

REFERENCES

Bath, G.T., Pringle, J.E., Whelan, J.A.J.: 1980, Monthly Notices Roy. Astron. Soc. 191, 185.

Breysacher, J., Vogt, N.: 1980, Astron. Astrophys. 87, 349.

Chiappetti, L., Tanzi, E.G., Treves, A.: 1980, Space Sci. Rev. 27, 3.

Cordova, F.A., Riegler, G.R.: 1979, Monthly Notices Roy. Astron. Soc. 188, 103.

Deeming, T.J.: 1975, Astrophys. Space Sc. 36, 137.

Cowley, A.P., Hutchings, J.B., Crampton, D.: 1981, Astrophys. J. 246,489.

Giacconi, R. et al: Astrophys. J. 230,540.

Grindlay, J.E.: 1980, private communication.

Hutchings, J.B., Crampton, D., Cowley, A.P., Thorstensen, J.R., Charles, P.A: 1981, preprint.

King, A.R, Lasota, J.P.: 1979, Monthly Notices Roy. Astron. Soc. 188,653.

Kraft, R.P., Krzeminski, W.: 1962, in Annual Report of the Director of Mount Wilson and Palomar Observatories (1961-1962), p. 20.

Krzeminski, W., Priedhorsky, W., Tapia, S.: 1981, private communication.

Masters, A.R., Pringle, J.E., Fabian, A.C., Rees, M.J.: 1976, Monthly Notices Roy. Astron. Soc. 178, 501.

Motch, C.: 1981, ESO preprint no. 135.

Papaloizou, J., Pringle, J.E.: 1980, Monthly Notices Roy. Astron. Soc. 190 (Short Comm.), 13P.

Patterson, J.: 1979a, Astrophys. J. Letters 233, L13.

Patterson, J.: 1979b, Astrophys. J. 234, 978.

Patterson, J.: 1979c, Astron. J. 84, 804.

Patterson, J.: 1981, Santa Cruz Summer Workshop on Cataclysmic Binarias.

Patterson, J., Branch, D., Chincarini, G., Robinson, E.L.: 1980, Astrophys. J. Letters 240, L133.

Patterson, J., Garcia, N.: 1980, IAU Circ. No. 3514.

Patterson, J., Price, C.M.: 1981, Astrophys. J. Letters, 243, L83.

Quinley, R., Africano, J.L., Rogers, W.: 1980, Bull.Am.Astr.Soc. 12,848.

Rappaport, S., Joss, P.C.: 1977, Nature 266, 683.

Robinson, E.L., Nather, R.E., Patterson, J.: 1978, Astrophys. J. 219,168.

Schwartz, D.A., Bradt, H., Biel, U., Doxey, R.E., Fabbiano, G., Griffiths, R.E., Johnston, M.D., Margon, B.: 1978, Astron. J. 84, 1560.

Sherrington, M.R., Lawson, P.A., King, A.R., Jameson, R.F.: 1980, Monthly Notices Roy. Astron. Soc. 191, 185.

Shipman, H.L.: 1977, Astrophys. J. 213, 138.

Stockman, H., Liebert, J., Tapia, S., Green, R., Williams, R., Ferguson, D., Szkody, P.: 1981, IAU Circ., No. 3616.

Vogt, N.: 1980, Astron. Astrophys. 88, 66.

Vogt, N., Krzeminski, W., Sterken, C.: 1980, Astron. Astrophys. 85,106.

Walker, M.F.: 1956, Astrophys. J. 123, 68.

Warner, B.: 1972, Monthly Notices Roy Astron. Soc. 158, 425.

Warner, B., McGraw, J.T.: 1981, Monthly Notices Roy. Astron. Soc. 196 (Short Comm.), 59P.

Watson, M.G., Sherrington, M.R., Jameson, R.F.: 1978, Monthly Notices Roy. Astron. Soc. 184 (Short Comm.), 79P.

White, N.E., Marshall, F.E.: 1980, IAU Circ. No. 3514.