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van der Klis, M.B.M.; Bonnet-Bidaud, J.M.

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Letter to the Editor

A Change in Light Curve Asymmetry and the Ephemeris of Cygnus X-3

M. van der Klis[1] and J. M. Bonnet-Bidaud[2]

[1] Astronomical Institute, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam; Cosmic Ray Working Group, Leiden, The Netherlands

[2] Section d'Astrophysique, CEN Saclay, DPh-EP/SAp, F-1190 Gif-sur-Yvette, France

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SUMMARY: Cygnus X-3 was observed in the 2-12 keV range for 40 days in May-June 1980. The mean 4.8 h light curve was seen to change significantly in a way suggestive of the existence of an underlying binary with an eclipse duration of 40 % of the period. The observed time of X-ray minimum was found to increase the level of confidence of a period derivative when compared to the earlier measurements.

Key words: X-ray sources - Cygnus X-3 - COS-B .

INTRODUCTION

Recent observations of Cygnus X-3 have led to an ephemeris with a significant period derivative (Manzo et al. 1978, Lamb et al. 1978, Elsner et al. 1980). Such a result, however, is only marginally consistent with the Copernicus phase determinations over four years (Mason and Sandford 1979, Mason, private communication). Ever since its discovery, the 4.8 h X-ray modulation itself, apart from the intensity and amplitude variation, was reported to have a stable asymmetric shape when averaged over many cycles (Mason et al. 1976b, Holt et al. 1979, Elsner et al. 1980).
The results on period and light curve symmetry variations are both important to distinguish between the various models proposed for Cygnus X-3 (see Elsner et al. 1980). In this letter we report new results obtained during recent X-ray observations of Cygnus X-3 by COS-B, which are relevant to the present discussion about the period derivative and demonstrate the existence of a stable, more symmetric type of light curve.

OBSERVATIONS

The X-ray detector on board the ESA COS-B satellite is an 80 cm^2 proportional counter with a 2-12 keV energy range and a 10^o FWHM field of view (see Boella et al. 1974). Data are recorded during a 25.4 s integration time every 102.4 s over the full 24 h active part of the 36 h satellite orbit, which therefore covers about 5 of the 4.8 h cycles of Cygnus X-3. Background substraction is performed using correlation formulae derived from pointings to empty fields (Bonnet-Bidaud and van der Klis 1979) and is accurate to about 0.5 c/s.
The instrument was pointed to the Cygnus region for 40 days from May 14 to June 23, 1980. The pointing direction was $\alpha=309^o$ and $\delta=40^o.5$, which kept Cygnus X-3 near the maximum sensitivity of the detector. The counting rate due to contaminating X-ray sources in the field of view, including Cygnus X-1, is estimated to less than 1 c/s.
The observations cover about 110 cycles of the 4.8 h modulation. Apart from the cycle to cycle variability, the mean 2-12 keV flux and the amplitude of the modulation increase respectively from 13 to 51 c/s and 3.5 to 20 c/s from May 14 to June 19, and then start to decrease (1 COS-B c/s ~ 2.9 10^{-10} erg $cm^{-2}s^{-1}$ (2-12 keV) for a Crab spectrum).
These values are similar to those obtained by other observers (Leach et al. 1972, Parsignault et al. 1977). The time of maximum intensity is in general accordance with long time periodicities as claimed by Holt et al. (1979) and Molteni et al. (1980).

RESULTS

a) The 4.8 hour light curve.

To study the mean shape of the light curve, we folded the data in one-week intervals modulo the period derived from the quadratic ephemeris of Elsner et al. (1980). In this way, the average light curves obtained do not depend sensitively on the ephemeris used and the cycle to cycle variability is adequately averaged out. As the mean flux and amplitude of the modulation vary considerably within our observation, the averaged curves were first fitted to a sine wave and then plotted as directly comparable, zero mean, unity amplitude histograms. The results for two different one-week intervals are given in figure 1 together with the normalization factors.
The first curve was obtained in the first week of the observations, when the mean flux was 14.3±0.1 c/s. Its shape is quite compatible with the asymmetric gradual-rise, steep-decrease light curve observed before (Parsignault et al. 1977, Mason et al. 1976b, Elsner et al. 1980). The second mean histogram, corresponding to a mean source flux of 41.4±0.1 c/s, has clearly a much more symmetric shape, in particular around maximum. The lower part (phase 0.8-1.2) is similar in the two curves.
We compared these two curves to the best-resolved light curve published previously on the basis of 1972-1974 Copernicus data (Mason et al. 1976a). The residuals to this curve were tested against a zero level using a χ^2-test. The resulting χ^2 values for 98 degrees of freedom are $\chi^2_\nu=0.96$ (P=58%) and $\chi^2_\nu=2.27$ ($P<10^{-9}$) respectively for the first and the second lightcurve. For the second curve, the deviation has a clear phase dependence, it is appreciable only around maximum (ϕ=0.2-0.8).
It is noted that this mean shape change is correlated to a nearly three-fold increase of mean flux and amplitude; also the ratio of the zero level and amplitude of the best-fit sine wave, which is commonly observed to be independent of the intensity (Parsignault et al.

Send offprint requests to: M. van der Klis

1977, Mason et al. 1976b), increases from 0.30±0.03 to 0.46±0.01.
The other one-week foldings exhibit a similar behaviour, the deviation from the 'standard' light curve being generally larger as the mean flux, amplitude and their ratio (modulation depth) increase.

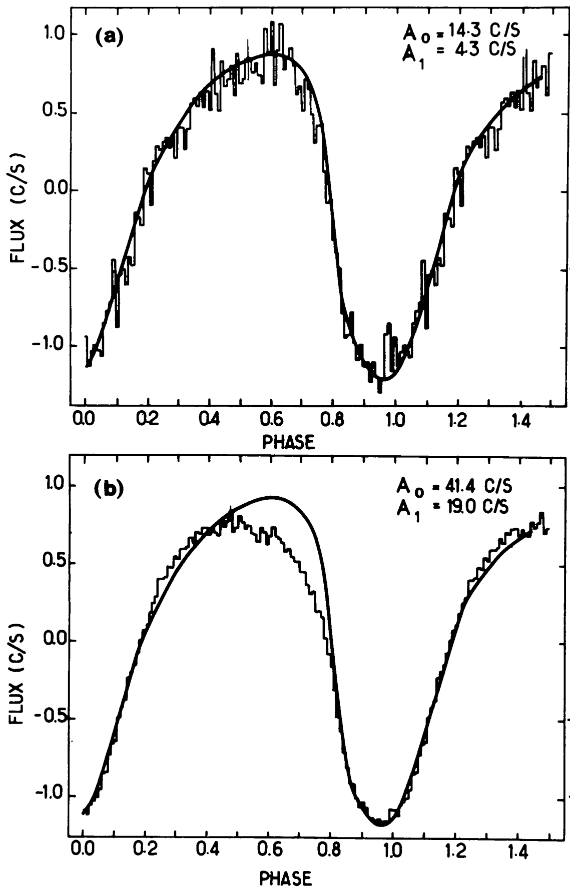

Figure 1 *Two folded light curves of Cygnus X-3 plotted on a normalized scale. Curve (a) was obtained between JD 2444373.9 and JD 2444380.5; curve (b) between JD 2444 2444398.0 and JD 2444404.8.*
Each curve is the avergage of 21 individual 4.8 h cycles. Error bars were computed from the dispersion in each phase bin.
Amplitude (A_1) and mean flux (A_0) of the best fit sine-wave to the folded light curve before normalizing are indicated.
Drawn line is representative of the light curve from previous observations from Mason et al. (1976a). Notice the symmetric top of the second curve and the stability of the lower part.

b) The 4.8 hour period.

Due to the shape variability reported above we find that a spurious phase shift of the time of X-ray minimum T_{min} determined from a sine fit, can be induced. Phase shifts of the order of -0.02 between the first, standard-shape, light curve and the later parts of our observation are found. Therefore we have used only the first week of the data to derive an accurate T_{min} and compare to other experiments.
To reduce the effect of intensity variations, we first normalized the flux in each satellite orbit (~5 cycles) by substracting the mean and dividing by the amplitude of the signal. A function of the form $A_0 + A_1$ sin $(2\pi\ (t-T_{min})/P - \pi/2)$ with A_0, A_1, T_{min} and P as free parameters, was then fitted to the data between JD 2444373.9 and JD 2444380.5.
The best fitting values were T_{min} = JD 2444377.4906±0.0009 and P=0.199903±0.000010d, with χ^2_ν = 1.7 for 3086 degrees of freedom. The errors were computed at a 1σ level according to the number of free parameters (Lampton et al. 1976). T_{min} values were corrected to refer to the barycenter of the solar system; the same is assumed for the published determinations quoted below. As the interval was rather short to determine the mean period, we have also used a fixed value for the period of 0.199679±0.000003 d, determined from a 4 parameter fit to the full observation. The new value for T_{min} was JD 2444377.4907±0.0007 showing that this parameter is insensitive to the exact value of P in this case.

We compiled the data gathered by Elsner et al. (1980) from several satellite experiments and the Copernicus results published by Mason and Sandford (1979). These measurements all refer to, or were corrected by the authors to refer to, the T_{min} of the best fit sine wave to the full light curve.
While Elsner et al. (1980) conclude to a $\dot{P}$ of (1.78±.40) 10^{-9}, and Mason and Sandford (1979) find a 3σ upper limit of 1.92 10^{-9} (the number quoted in their letter should be increased by a factor of five, Mason, private communication), a parabolic fit of the form $\phi = (t-T_{min})/P_0 - ((t-T_{min})/P_0)^2.\dot{P}/2$ through all the compiled T_{min} determinations leads to a value of $\dot{P}$ = (1.50±0.22) 10^{-9}. The associated χ^2_ν is 1.37 at 56 degrees of freedom, while a constant period hypothesis gives a minimum χ^2_ν of 1.46 at ν=57. Applying the F-test to these χ^2 values, we find a probability of 3.4% that this $\dot{P}$ is spurious and should really be zero.

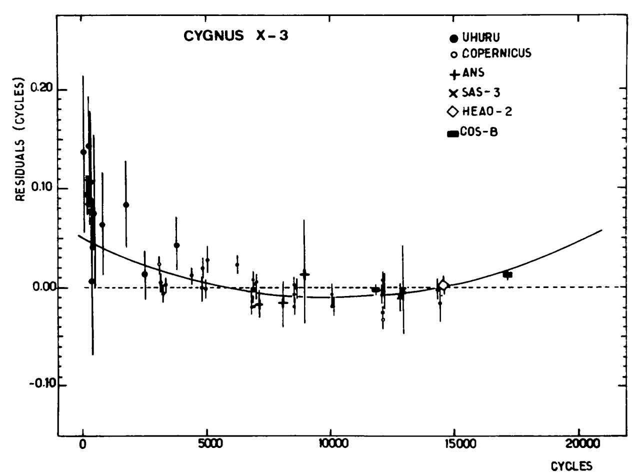

Figure 2 *Nine years of measurements of the phase of the minimum of the 4.8 h light curve. The residuals with respect to the best fitting linear ephemeris (dashed line) are shown together with the best fitting parabola ($\dot{P}$ = 1.18 10^{-9}, see table).*

Adding the present T_{min} measurement, and thereby extending the baseline over which T_{min} was monitored from 14567 to 17165 cycles with a relatively accurate point, (fig. 2), we now find $\dot{P}$=(1.18±0.14) 10^{-9} (see table for the full ephemeris). The probability for $\dot{P}$ to be zero now is less than 0.01% according to the F-test (see the χ^2 values in the table).
Nevertheless there is still a larger scatter around the best fitting parabola than justified by the quoted errors on the individual T_{min} determinations, as re-

flected by the high χ^2_ν of 1.4. We cannot exclude intrinsic changes in the 4.8 h clock itself, but this scatter could also be due to unnoticed shape variations of the kind presented above.

Table

Temporal parameters of best sine-wave fit in COS-B observations.

T_{min} = JD 2444377.4907 ± 0.0007

P = 0.199679 ± 0.000003 days

Best-fit ephemerides for the combined T_{min} determinations from Elsner et al. (1980), Mason and Sandford (1979) and the present paper.

P constant	T_0 =	JD 2440949.8887 ± 0.0009
	P =	0.1996854 ± 0.00000006 d
	χ^2_ν =	2.58 at ν = 58
$P = P_0 + \dot{P}.t$	T_0 =	JD 2440949.8986 ± 0.0030
	P_0 =	0.1996830 ± 0.0000004 d
	$\dot{P}$ =	(1.18 ± 0.14) 10^{-9}
	χ^2_ν =	1.41 at ν =57

DISCUSSION

The asymmetry of the light curve can be explained by an asymmetric distribution of gas in the system or by an elliptical orbit for the X-ray source surrounded by a symmetric cloud (see Elsner et al. 1980).
In the latter case, apsidal motion could cause a change of the asymmetry of the light curve (Ghosh et al. 1980). As this would be a gradual process on a timescale of years, this cannot be an explanation of the presented effect. The observational facts to explain are three fold:

- a large increase of the 2-12 keV flux, in coincidence with
- a more symmetric X-ray maximum, and
- relatively deeper X-ray minima.

Model calculations by Hertz et al. (1978) relate the depth of the X-ray minimum to the effective optical depth τ_e of the gas around the system, in the case that the underlying object is an eclipsing binary. For lower τ_e, the relative depth of the minimum increases, due to an increase of the number of unscattered photons which reach the observer during the non-eclipsed part of the binary cycle. This holds both in the context of a 'cocoon' - or a stellar wind model. The observed change of modulation depth could already be explained by a change of τ_e from, say, 1.0 to 0.5, depending on the model.
In this way, for lower τ_e the light curve would also tend to become symmetric around maximum, more like the underlying eclipsing binary light curve. As we only observe this effect between phases 0.2 and 0.8, the rest of the cycle would correspond to X-ray eclipse. If we assume that the observed increase of the 2-12 keV flux is correlated to a lower τ_e (for example by a change in the underlying spectrum resulting in a different ionization of the surroundig gas), this would be an explanation of the presently observed effects.

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