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The research supported by this grant may be summarized in two documents, copies of which are attached. The first document is an abstract of a paper presented by the principal investigator at the April 1978 meeting of the American Physical Society. The second document is a paper which has been accepted for publication by the Astrophysical Journal (Letters) and which is scheduled to appear in the 1 April 1979 issue.

R. C. Lamb, March 2 1979

Richard C. Lamb
Department of Physics
Iowa State University

THE PERIOD DERIVATIVE OF CYGNUS X-3

R. C. Lamb,* R. G. Dower,† and R. K. Fickle*

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ABSTRACT

X-rays from Cygnus X-3 have been observed during early 1978 with the detectors of the SAS-3 satellite. These observations, in conjunction with earlier URURU and ANS data, indicate that the 4.8 hr period of Cygnus X-3 is increasing at a rate of $\dot{P}/P = (5.1 \pm 1.3) \times 10^{-6}\ yr^{-1}$. The sign and magnitude for this change are incompatible with a rotation model for the period and are in reasonable agreement with model predictions for orbital changes associated with mass loss and transfer in a binary system.

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* Department of Physics, Iowa State University, Ames, Iowa 50011

† Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Abstract Submitted

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Search for X-Ray Emission from the γ-Ray Source γ195+5. R. C. LAMB, Iowa State Univ. and R. C. DOWER, M.I.T.--The high energy (≥ 100 MeV) γ-ray source, γ195+5, observed by both the SAS-2 and COS-B satellites with an intensity approximately equal to that of the Crab, has so far elluded detection at other wavelengths. In an effort to establish a possible X-ray identification an observation with the SAS-3 rotation modulation collimators was conducted January 5-12, 1978. Preliminary results show no X-ray source of greater than 6σ significance within either the SAS-2 or COS-B 90% error boxes, corresponding to an upper limit of the X-ray intensity in the 2-11 keV range of less than 1μJy (∿1 Uhuru ct/sec). Comparison of this result with unpublished OSO-8 evidence for an X-ray source in this region and recent SAO work will also be presented. This work was supported in part by the National Aeronautics and Space Administration.

Richard C. Lamb

R. C. Lamb
Physics Department
Iowa State University
Ames, Iowa 50011

(✓) Prefer Standard Session

I. INTRODUCTION

The 4.8 hour periodic variation in the X-ray intensity of Cygnus X-3 has been observed since late 1970. We present observations from the SAS-3 satellite taken during early 1978 which, in conjunction with earlier data (Parsignault, et al., 1976, Leach, et al., 1975), show evidence for a non-constant period. A simple interpretation of these data is that the period of Cygnus X-3 is increasing with time at a rate $\dot{P}/P = (5.1 \pm 1.3) \times 10^{-6}\ yr^{-1}$ consistent with the previous authors' upper limits. The sign and magnitude for this change are incompatible with a rotation model for the period, and are in reasonable agreement with predictions by Davidsen and Ostriker (1974) and Pringle (1974) for orbital changes associated with mass loss and transfer in a binary system.

II. OBSERVATIONS AND RESULTS

Cygnus X-3 was observed with the slat detectors of the SAS-3 satellite (Buff et al., 1977). From 1978 January, 5.9 to 12.0 (UT) the source was scanned once per satellite orbit (~94 min.) while another region of primary interest was observed with the rotation modulation counter system on the satellite's spin axis. During these observations, Cygnus X-3 varied from 21° to 27° from the scan plane, and the relative efficiency of the center detector varied between 0.39 and 0.32. The results of these observations are shown in Figure 1a, in which the source counting rate, corrected for elevation, is plotted versus the 4.8 hour phase. Phase 0.0 corresponds to the minimum of the fitting function: $I = A_o + A_1 \sin[\omega(t - t_{min}) - \frac{\pi}{2}]$ as used by Parsignault *et al.* (1976), so I is a minimum at $t = t_{min}$. The source intensity was determined directly from counting rate plots in which the intensity is proportional to the height of a triangle response above a smooth background. The peak height varied from ∿ 1 to 4 mm above background on the plots corresponding to a counting rate of ∿ 6 to 24 cts/s. The estimates of error indicated in the figure include a constant error of ± 1/3 mm (2 cts/s) in the background determination and a "statistical" error proportional to the square root of the peak height. The work of Parsignault *et al.* (1977) has shown that there are intensity fluctuations larger than those to be expected on the basis of statistics alone. Our data qualitatively support this conclusion. In order to achieve a χ^2 per degree of freedom of ∿ 1 for the data points near minimum phase (0.85 to 0.25) where the excessive fluctuations are minimized, it is necessary to increase the "statistical" error by about a factor of two from a value which would be consistent with counting statistics alone. If this adjustment were not done then the errors associated with fitted parameters would be somewhat underestimated. The error estimates shown in the figure include this adjustment.

The values of $P = 2\pi/\omega$ and t_{min} from the fit restricted to the 30 points with phases between ∿ 0.85 and 0.25 are shown in Table 1. Values of P and t_{min} from a fit to all 76 points do not differ appreciably from these values. The fitted counting rate at phase 0.0 was 20 ± 2 cts/s, corresponding to an intensity over the interval 1.5 to 6 keV of $\sim 2.2 \times 10^{-9}$ erg cm^{-2} s^{-1} for a Crab-like spectrum.

The second set of observations span a week beginning 1978 January 26.8. Four observations of Cygnus X-3 were made near the beginning of the week and seven near the end. For comparable phases there was no significant difference in the intensity. Therefore we have combined these 11 observations and plotted them in Figure 1b. The errors associated with these points are smaller than the January 6-12 data principally because Cygnus X-3 was near the scan plane where detector efficiencies are nearly 1.0 and the counting rates were correspondingly larger. The fitted value of the counting rate at phase 0.0 is 18 ± 2 cts/s consistent with the early January observations. The values of P and t_{min} from a fit to all 11 points is shown in Table 1. If the fit is restricted to those points with phases approximately between 0.85 and 0.25, then only 5 points remain to determine a function with 4 free parameters. This procedure was not considered satisfactory. If A_0 and A_1 are taken from the 11 point fit then a satisfactory fit to P and t_{min} are obtained with only the 5 points between phase 0.85 and 0.25, and the values of P and t_{min} do not differ appreciably from the table values. However, the error on t_{min} is somewhat greater than that obtained in the 11 point case, and this error is the one we have chosen to list. Both values of t_{min} shown in Table 1 are referenced to the barycenter of the solar system; the values of the correction necessary are $0^d.0024$ and $0^d.0030$ respectively. It is assumed that previous determinations of t_{min} include this correction.

If we assume that the difference in the two values is a whole number of periods (106) then a period of $0^d.19969 \pm 0.00009$ over this 21 day interval is obtained. This accuracy of $\sim$ 1 part per 2000 is comparable to earlier determinations of the period over a similar time interval, furthermore the value of the period agrees with previous determinations. The near constancy of the period allows one to extrapolate over those intervals of time in which Cygnus X-3 has not been observed to determine the total number of cycles from a given epoch with confidence that no cycles have been missed nor spurious cycles introduced. Therefore, one can tie together previous observations to arrive at a more precise period and test for a period derivative (Parsignault _et al._, 1976, Leach _et al._, 1975). We assume the period varies linearly with time as: $P(t) = P_o + \dot{P}t$. The phase, ϕ, in cycles, at an arbitrary time, t, after a reference time, t_o, may be expanded as: $\phi = \Delta t/P_o - \frac{1}{2}\dot{P}(\Delta t)^2/P_o^2$ where $\Delta t = t - t_o$. Our values of t_o, ϕ, and the error on ϕ, along with previous determinations, are listed in Table 2. Also listed are the values of ϕ_{fit} taken from a least squares fit to these observations. The values of the parameters determined from the fit are:

$$P_o = 0\overset{d}{.}1996795 \pm 0.0000007$$

$$\dot{P}/P_o = (5.1 \pm 1.3) \times 10^{-6}\ yr^{-1}$$

$$t_o = \text{JD } 2,440,949.9173 \pm 0.0010$$

The residuals from the fit are shown in Figure 2. The χ^2 for the fit is 12.5 for 14 degrees of freedom. The χ^2 for a linear fit with $\dot{P} \equiv 0$ is 29.3. The likelihood ratio of the quadratic to the linear fit is given by $\exp[-(\chi^2_{quad.} - \chi^2_{lin})/2] \cong 4400$ to 1, equivalent to a 3.7σ result on a non-zero period derivative. The χ^2 for the quadratic fit is at the 56% confidence level with none of the data points contributing excessively. This is evidence that the simple variation of the period with time that we have assumed is entirely adequate to fit the seven years of observations. In particular there is no evidence for significant discontinuities or jumps in the phase as might be expected if the 4.8 hr period is the rotational period of a neutron star undergoing glitches.

III. DISCUSSION AND CONCLUSIONS

The observation of an increase in the period of Cygnus X-3 with a time scale $P/\dot{P} \approx 2 \times 10^5$ yr places a constraint on various models which may be proposed. One possibility which would appear to be ruled out is that the 4.8 hour period is the rotational period of a neutron star. If the X-rays are from accreting matter from a binary companion onto the neutron star then, using the analysis of Rappaport and Joss (1977), we estimate that accretion torques would generally accelerate the rotation on a time scale of ~ 1 yr. Our observations are clearly inconsistent in magnitude <u>and</u> sign with such a model.

The most popular view of Cygnus X-3 is that the 4.8 hour period is the orbital period of a close binary. If one assumes a circular orbit then the separation of the two components is $1.0 \times 10^{11} (M_{total}/M_{\odot})^{1/3}$ cm. Mass transfer and mass loss will alter the separation and hence the period, however there is no unique, model-independent relationship between mass changes and period changes (e.g. Thomas 1977; Paczyński 1971). Of the models for Cygnus X-3 in the literature (Davidsen and Ostriker, 1974; Pringle, 1974; Basko, Sunyaev and Titarchuk, 1974; Milgrom, 1976; van den Heuvel and De Loore, 1973) only the first two give estimates of the time scale for possible period changes.

In the model of Davidsen and Ostriker (1974) the X-rays originate in the accretion of a stellar wind onto a white dwarf, and the wind itself modulates the X-rays to give rise to the observed periodicity. Their lower limit on $\dot{P}/P$ is $+3 \times 10^{-6}$ yr^{-1} which is in good accord with our observation. However, the observation of $\sim$ 100 MeV γ-rays from Cygnus X-3 (Lamb et al., 1977) has made it more likely that the compact object is a neutron star rather than a white dwarf, in view of the evidence that pulsars (neutron stars) can emit γ-rays (Ögelman, et al., 1976) and the absence of any positive evidence for such emission from white dwarfs. If the compact object is a neutron star then its rotational period may provide an additional modulation to that fraction of the X-rays which come directly from the neutron star and are not scattered appreciably. Serlemitsos et al. (1975) have placed an upper limit of 3% on the fraction of pulsed X-rays with periods in the range of 2 ms to several seconds. For periods from 2 to 64 s the upper limit is 10% (Parsignault et al., 1977) however we are unaware of any efforts to search for longer periods and suggest that such efforts may be worthwhile.

The model of Pringle (1974) is similar to that of Davidsen and Ostriker in that the primary X-rays result from accretion of a stellar wind onto a compact object, and a time scale of 10^6 yr is suggested. Thus both stellar wind models accord with the observed value of $\dot{P}/P$.

One feature of stellar wind models is that the observed X-ray spectra should be somewhat phase dependent, in particular the absorption should vary with the 4.8 hr phase (Davidsen and Ostriker, 1974). Previous studies had shown no such effect, however recently Becker et al.

(1978) have observed phase dependent spectral changes in the X-ray emission which are qualitatively consistent with such models.

If we accept the view that the compact object is a neutron star, then we find that the X-ray luminosity of Cygnus X-3, at an assumed distance of 10 kpc (Lauqué, Lequeux, and Rieu 1972), may be maintained with a mass accretion rate of typically $\sim 3 \times 10^{-9}\ M_{\odot}\ yr^{-1}$. This rate is too small by a few orders of magnitude to account for the observed period changes. For typical binary parameters the absolute value of the fractional change in the period due to mass transfer (accretion) is comparable to the fractional mass transferred (Thomas 1977). Therefore, if the mass accretion rate we have given is a valid estimate, then one can say that the observed changes in the period of Cygnus X-3 are not primarily associated with accretion but rather are driven almost exclusively by mass loss from the system. An estimate of the mass loss rate may be obtained by using the relation derived by Davidsen and Ostriker for the case where there is negligible mass transfer and where the mass lost carries away its angular momentum. Under these circumstances $\dot{M}_t/M_t = -\frac{1}{2}\dot{P}/P$ where M_t is the total mass of the system. If we assume a system mass of 2 $M_{\odot}$, then the observed value of $\dot{P}/P$ implies a mass loss rate of $\sim 5 \times 10^{-6}\ M_{\odot}\ yr^{-1}$.

In summary, the observed period increase appears to support a binary origin to the 4.8 hr period with reasonable agreement in sign and magnitude to the detailed predictions of Davidsen and Ostriker (1974).

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After this work was completed, we became aware of COS-B observations (Manzo, Molteni, and Robba 1978) which, in conjunction with the earlier UHURU and ANS data, give a value of $\dot{P}/P = (5.2 \pm 1.2) \times 10^{-6}\ yr^{-1}$. Their other parameters, P_0 and t_0, are also in excellent agreement with ours.

TABLE 1

SAS-3 OBSERVATIONS OF CYGNUS X-3

Time of Observation	Fitted Period	Fitted Time of Minimum Intensity (JD 2,440,000+)
1978 January 6-12	$0^{d}.19987 \pm 0.00029$	3517.6420 ± 0.0033
1978 January 26 -February 2	$0^{d}.19947 \pm 0.00028$	3538.8090 ± 0.0090

TABLE 2

SUMMARY OF OBSERVATIONS USED TO DETERMINE $\dot{P}$

Time of Minimum Intensity (JD 2,440,000+)	Reference	Phase of Minimum Intensity, ϕ (cycles)	Error in ϕ	Phase calculated from the quadratic fit
949.9183	a	0.0	0.081	0.005
987.6629	a	189.0	0.019	189.030
988.4555	a	193.0	0.032	193.000
991.6625	a	209.0	0.046	209.061
1022.9995	a	366.0	0.007	365.997
1024.7890	a	375.0	0.029	374.959
1025.7805	a	380.0	0.074	379.924
1031.1685	a	407.0	0.079	406.907
1107.6697	a	790.0	0.056	790.027
1304.3573	a	1775.0	0.047	1775.040
1450.1143	a	2505.0	0.025	2504.990
1697.1296	a	3742.0	0.030	3742.038
2371.4484	b	7119.0	0.013	7118.992
2552.3637	b	8025.0	0.025	8025.000
2737.8773	b	8954.0	0.050	8954.035
3517.6420	c	12859.0	0.017	12859.000
3538.8090	c	12965.0	0.045	12965.000

[a] Leach et al. 1975.

[b] Parsignault et al. 1976.

[c] This work.

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FIGURE CAPTIONS

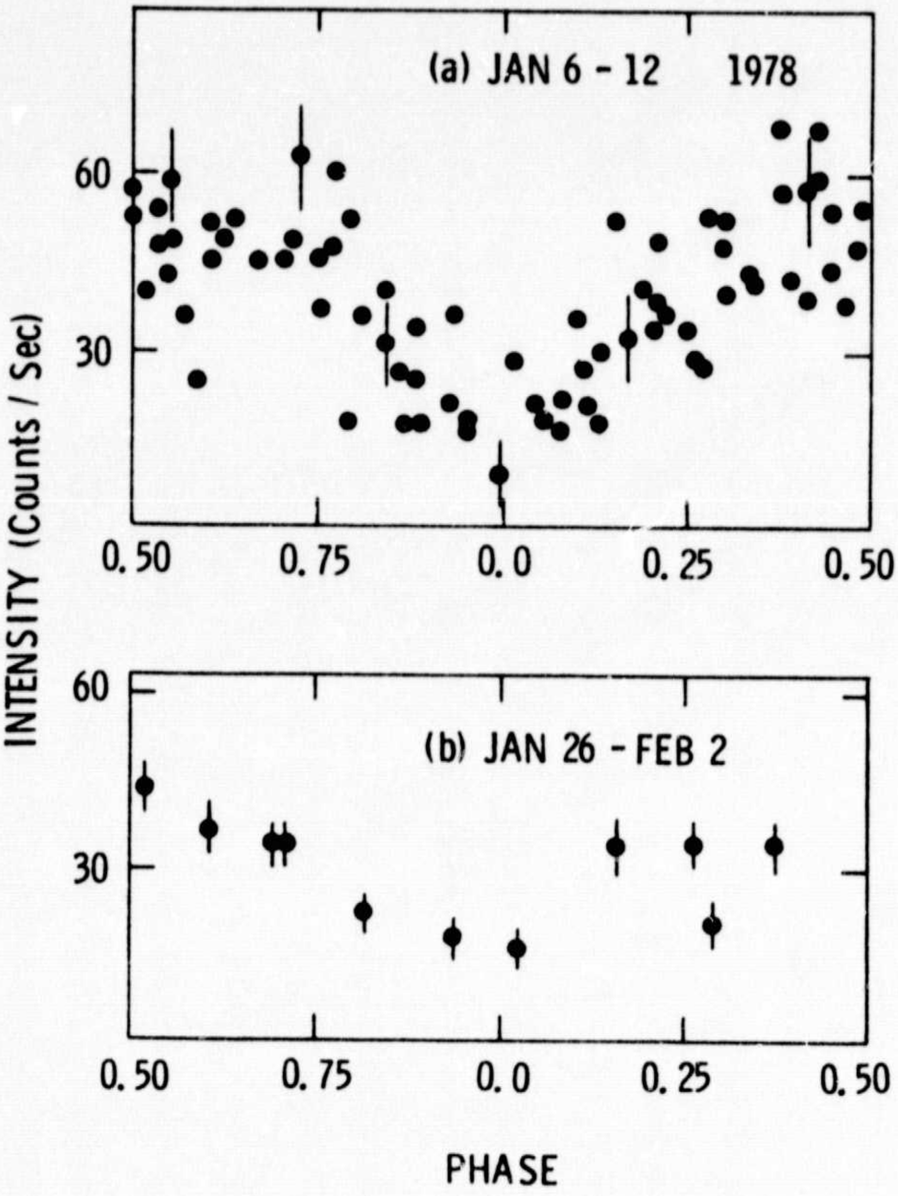
Figure 1a,b:

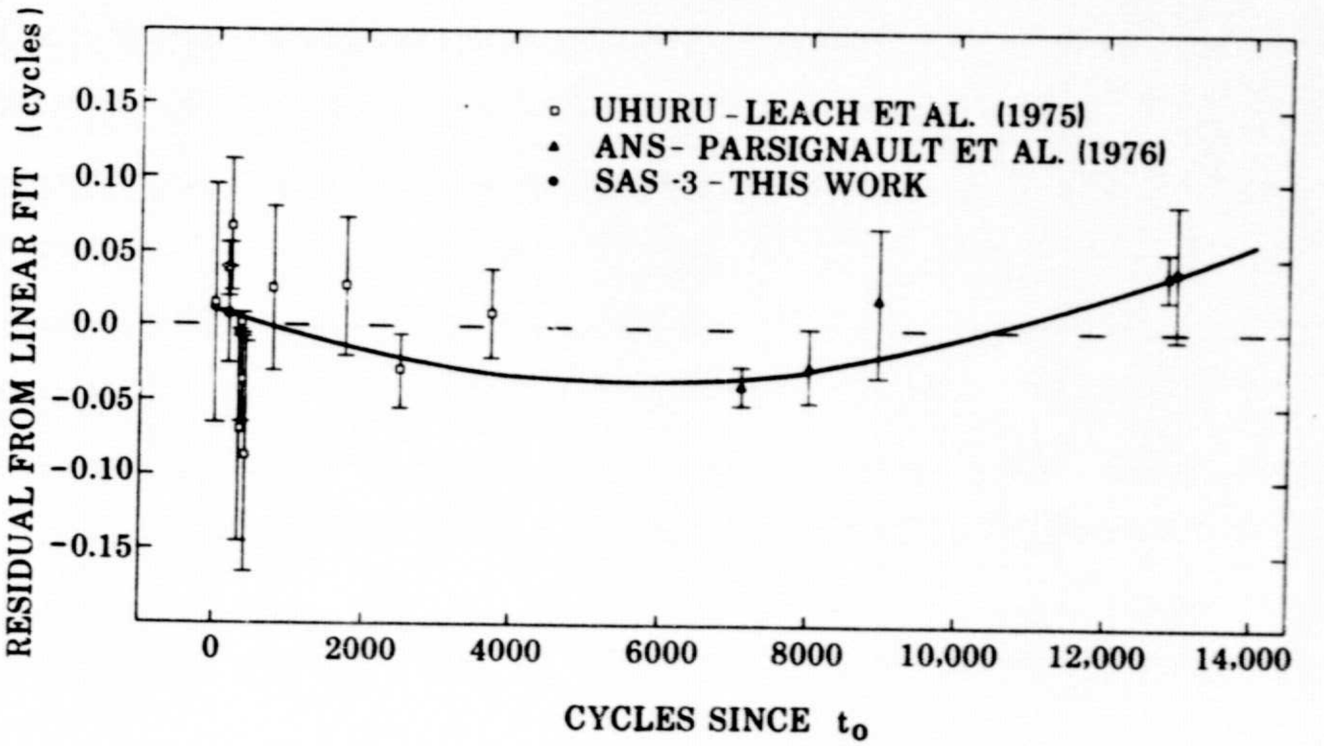
The phase dependence of the X-ray intensity from Cygnus X-3 Jan. 6-12 1978 and Jan. 26-Feb. 2 1978 respectively. Phase 0.0 corresponds to the minimum of the fitting function:

$$I = A_0 + A_1 \sin [\omega(t - t_{min}) - \frac{\pi}{2}].$$

Figure 2:

Residuals from both a linear fit and a quadratic fit to the observations of Cygnus X-3 phase minima by UHURU, ANS, and SAS-3 (this work) over a 7 year period. The residuals to the linear fit are measured from the dashed line; $\chi^2_{linear} = 29.3$. The residuals from the quadratic fit are measured from the solid curve; $\chi^2_{quad.} = 12.5$. The linear fit assumes $\dot{P} \equiv 0$ whereas the quadratic fit determines $\dot{P}/P$ to be $(5.1 \pm 1.3) \times 10^{-6}$ yr^{-1}.


(a) JAN 6 - 12 1978
60
30
INTENSITY (Counts / Sec)
0.50
0.75
0.0
0.25
0.50
(b) JAN 26 - FEB 2
60
30
0.50
0.75
0.0
0.25
0.50
PHASE



RESIDUAL FROM LINEAR FIT (cycles)
0.15
0.10
0.05
0.0
−0.05
−0.10
−0.15
0
2000
4000
6000
8000
10,000
12,000
14,000
CYCLES SINCE t_o
UHURU - LEACH ET AL. (1975)
ANS - PARSIGNAULT ET AL. (1976)
SAS -3 - THIS WORK