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Characteristics of the Cen X-3 Neutron Star from Correlated Spin-up and X-ray Luminosity Measurements

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Summary. Results are presented of one month of observations with the ESA COS-B satellite of the X-ray pulsation period of Cen X-3, together with X-ray luminosity measurements during this same time.

The data are shown to be compatible with an unbraked spin-up by accretion from a Keplerian disk onto a neutron star with $f = 4\mu_{30}^{2/7} R_6^{6/7} I_{45}^{-1} (M/M_\odot)^{-3/7} = 1.65 \pm 0.44$, and no braking occurring down to a luminosity of $L_x = 4.2_{10}37$ erg/s. The mean intrinsic luminosity during an observed turn-on episode is calculated from the high observed spin-up as $L_x = (9.0 \pm 2.6)_{10}37$ erg/s, which together with the long term behaviour of the pulsation period shows that certain low states of the source are in fact periods of high accretion.

It is argued that some current neutron star models are irreconcilable with the value of f determined in this paper. The present f determination is shown to imply a lower mass limit for the Cen X-3 neutron star of 1.1 $M_\odot$.

Key words: X-ray binaries – neutron stars – spin-up – COS-B

I. Introduction

The X-ray source Cen X-3, since its discovery in 1972 as an X-ray pulsar in a binary system (Giacconi et al., 1971; Schreier et al., 1972), has been relatively well studied both from the point of view of its luminosity (Pounds et al., 1975; Long et al., 1975; Schreier et al., 1976) and of its pulsation period behaviour (Tuohy, 1976; Fabbiano and Schreier, 1977).

In particular, it has been shown to exhibit OFF periods during which the source apparently decreases in intensity to a level comparable to the eclipses (Schreier et al., 1977). Several interpretations have been proposed to explain this behaviour in terms of a precessing disk (Holt et al., 1978), a change in the absorption by surrounding matter (Schreier et al., 1976) or an intrinsic change in the accretion rate.

The presence of an accretion disk was also suspected on the basis of the amount of angular momentum expected to be transmitted during the high states of the source and the observed changes in the X-ray luminosity (Bonnet-Bidaud and van der Klis, 1979, hereafter Paper 1).

On the other hand, the measured spin-up rate of the source (Fabbiano and Schreier, 1977) was found to be lower than the one expected from a standard accretion disk model with a neutron star (Pringle and Rees, 1972), and periods of slowing down were observed which require additional braking torques (Fabbiano and Schreier, 1977).

Since in X-ray binaries, the observed spin-up rate of the compact object, interpreted as a result of accretion is related to the angular momentum transmitted, a detailed study of the relation between period changes and luminosity of the X-ray source should allow us to put interesting constraints on both accretion models and compact object characteristics.

Some conclusions were already drawn from the measured spin-up rates for X-ray sources of different mean luminosities (Rappaport and Joss, 1977; Mason, 1977), but the large expected spread in the characteristics of these different systems has somewhat weakened the possible conclusions.

Here, we present data obtained with the high time resolution mode of the ESA COS-B satellite during a one-month continuous observation of Cen X-3 from December 24, 1975 to January 23, 1976. From these high time resolution data, we were able to study the pulsation period changes from one binary cycle to the next one. These results together with the overall monitoring of the source flux during the same period (see Paper 1), allow an interesting study of the correlation between pulsation period changes and the luminosity.

II. Analysis

a) Satellite

The COS-B satellite was pointed at the X-ray source Cen X-3 ($\alpha = 167\overset{\circ}{.}7$; $\delta = -60\overset{\circ}{.}3$) continuously between December 24, 1975 and January 23, 1976.

The satellite payload includes an X-ray detector which has been described by Boella et al. (1974). It is a collimated proportional counter with an effective area of 80 cm^2 at maximum response and an energy range from 2 to 12 keV with a peak value response around 6 keV; the collimated field of view is 10° FWHM with a flat top of $1\overset{\circ}{.}1$ wide. The X-ray photons detected are accumulated over 25.4 s intervals every 102.4 s for monitoring the source over the full month of observation. To allow a finer temporal analysis, the arrival times of the four (or eight, depending on telemetry constraints) first events in successive telemetric windows of 0.64 s are also recorded with an accuracy better than 0.25 ms.

This window sampling and the rejection of some part of the data because of contamination by charged particles, reduce the effective observing time in this high time resolution mode to about 10^5 s. The total number of recorded arrival times is about 10^7, but

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the limited efficiency of the rejection of charged particles makes the background contribution more than 50%.

b) Data Reduction

The X-ray arrival times in the high time resolution mode were used to study the 4.8 s pulsation period of Cen X-3.

The arrival times in the satellite frame were first corrected for the satellite and earth motion and transported from the satellite to the Solar System Barycenter (SBB) using the Lincoln Laboratory Ephemeris and the precise satellite position. This procedure was essentially the same as the one applied to the data from radio pulsars from the same satellite (Bennet et al., 1976; Bonnet-Bidaud and d'Amico, 1979). The resulting absolute accuracy after these corrections is about 0.5 ms.

Because of the relatively high background level and the low photon sampling rate, the accumulation of X-ray arrival times over periods of a few hours was necessary to determine the pulsation period with a good accuracy. Therefore a first correction using the literature values for the orbital parameters (Tuohy, 1976; Fabbiano and Schreier, 1977) was applied to correct the arrival times for the motion of the X-ray source with respect to the binary system barycenter during the integration intervals.

Phase histograms were then built using the distribution of the time intervals between successive events in each phase bin, since the average mean interval for source photons is 30 ms, much smaller than the Cen X-3 pulsation period. As the number of time intervals in each phase bin is always large, the mean of the distribution was taken to be the arithmetical mean and the corresponding counting rate:

$$n = N / \sum_{i=1}^{N} t_i$$

where N is the total number of time intervals in the phase bin, and t_i is the length of a time interval in the bin.

The light curves, resulting for different values of the period, were then tested against a curve of constant flux using a χ^2 test. The best value for the period was taken to be the one for which the χ^2 value was at its maximum, with an uncertainty corresponding to the width of the χ^2 peak at a 3σ statistical standard deviation level.

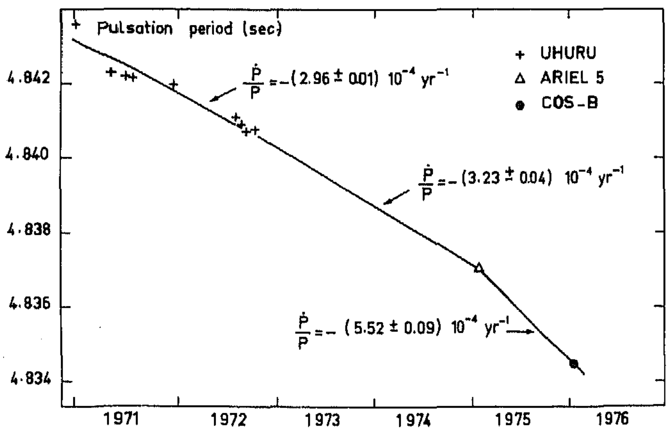

Fig. 1. The long term change in the pulsation period of Cen X-3. The COS-B point is a weighted mean determined for JD 2442785.3. Error bars are smaller than data points. The solid lines represent the measured mean change in pulsation period between separate observations, except for the 1971–1972 interval where the quoted number was determined by a weighted fit through the Uhuru observational points (Fabbiano and Schreier, 1977). The Ariel V determination is from Tuohy, 1976

c) Orbital Parameters

Using the method described above, a set of values for the pulsation period P_s was derived, combing several stretches of data to diminish the effect of orbital phase. The best fit to the points in the resulting plot of pulse period against time, representing the general trend in P_s was then subtracted from the individual points. The residuals still showed a slight dependence on orbital phase.

If we analyse the influence of the orbital period P_{orb}, the mid-eclipse time ϕ_o, and the projected radius of the binary orbit $A = a \sin i$ on the periodic change of the pulsation period due to a Doppler delay of the form:

$$\Delta t = A \sin\left(\frac{2\pi}{P_{orb}}(t - \phi_o) + \pi/2\right) \equiv A \sin \phi, \tag{1}$$

we find to first order:

$$\delta\left(\frac{\Delta P_s}{P_s}\right) = \frac{2\pi}{P_{orb}}\left(\delta A - \frac{A}{P_{orb}}\delta P_{orb}\right) + \frac{4\pi A^2}{P_{orb}^2}\left(\delta\phi_o + \frac{t - \phi_o}{P_{orb}}\delta P_{orb}\right)\sin\phi, \tag{2}$$

where the eccentricity of the orbit was taken to be zero.

The value of the factor A/P_{orb} is $2.2_{10} - 4$, $(t - \phi_o)/P_{orb}$ is 7 at most in the present observation. The best determination of A is 39.792 ± 0.005 light s (from 1972 Uhuru data, Fabbiano and Schreier, 1977), while during the time of observation P_{orb} is 2.08712 ± 0.00002 d and ϕ_o is known to an accuracy of $3_{10} - 3$ d (Paper 1). Therefore δP_{orb} is small enough to exclude it from further analysis, the factors $A\delta P_{orb}/P_{orb}$ and $(t - \phi_o)\delta P_{orb}/P_{orb}$ being an order of magnitude smaller than δA and $\delta\phi_o$, respectively.

A sinusoidal curve with this period was fitted to the residuals using the method of van Paradijs et al. (1977). After correction for the fact that each pulse period determination represents a finite binary phase interval the best zero phase time was determined to be JD 2442787.1755 ± 0.0007, the best projected orbital radius 39.71 ± 0.04 light s.

As pulse period determinations with these orbital parameters do not show any significant residual correlation with orbital phase, these were used in the subsequent data analysis.

The value for ϕ_o is in accordance with that of JD 2442787.177 ± 0.003, independently determined from the COS-B X-ray eclipse observations (Paper 1), A is in the range of the values deduced from Uhuru observations.

From the present determination of ϕ_o the mean binary period between the Ariel-V and COS-B observations is calculated to be 2.08711 ± 0.00002 d.

III. Results

a) Pulsation Period

After correction for the binary orbital motion in the above described way, the intrinsic pulsation period of Cen X-3 was determined to be $(4.834477 \pm 7_{10} - 6)$ s at the middle of the observation (JD 2442785.3).

Figure 1 shows how this value fits in with earlier observations (Tuohy, 1976; Fabbiano and Schreier, 1977). The mean spin-up between the Ariel-V and COS-B observations was $-\dot{P}/P = 5.52$

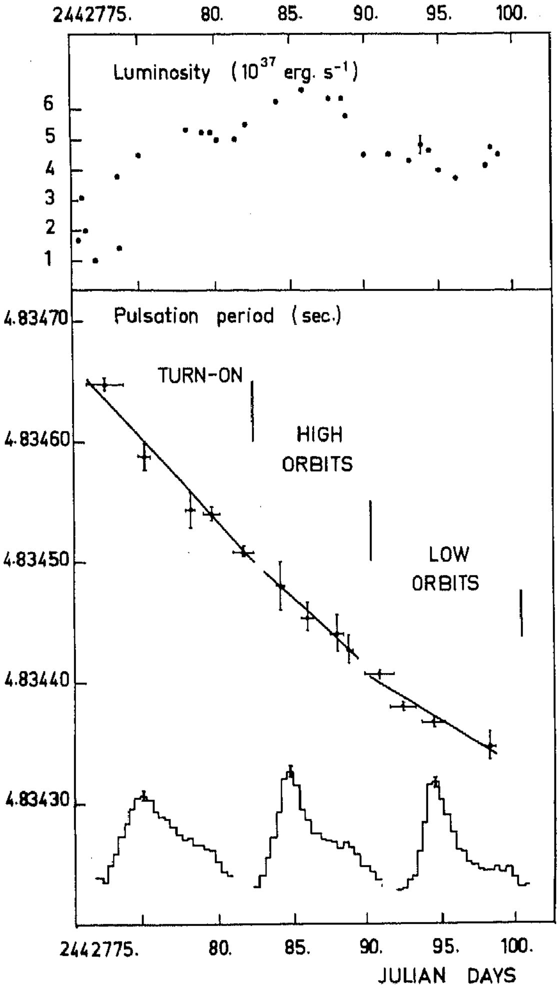

Fig. 2. The Cen X-3 pulsation period behaviour inside the COS-B observation. The pulsation period in each interval is determined as indicated in the text. One sigma error bars and the extension in time of each interval are shown. Both have been taken into account to determine the best linear fits (solid lines) through the three groups of points (see text). Values are quoted in Table 1. Also shown in the upper part of the figure, is the luminosity behaviour during the same time. Each luminosity point was determined from the detailed light curve (Paper 1). Typical error bar is shown. Three mean pulse profiles (see text) are shown in the lower part of the figure

$\pm 0.09_{10} - 4$ yr^{-1}, considerably higher than it was during the years 1971–1974 (about $3_{10} - 4$ yr^{-1}).

The COS-B data allow a much more detailed monitoring of the pulsation period during the time of observation. The results of this study are presented in Fig. 2, which also shows the X-ray luminosity of Cen X-3 during the same time. As can be seen from this figure, the mean spin-up is relatively high ($8.6 \pm 0.6_{10} - 4$ yr^{-1}), comparable to the 1971 August–September Uhuru observation (Fabbiano and Schreier, 1977), and higher than the long term spin-up between the observations of Ariel-V and COS-B. Also, the spin-up rate is seen to be changing during the COS-B observation: it is higher near the start and lower at the end of the observation. Therefore the month of observation has been divided in three parts and straight lines have been fitted to the pulsation period points

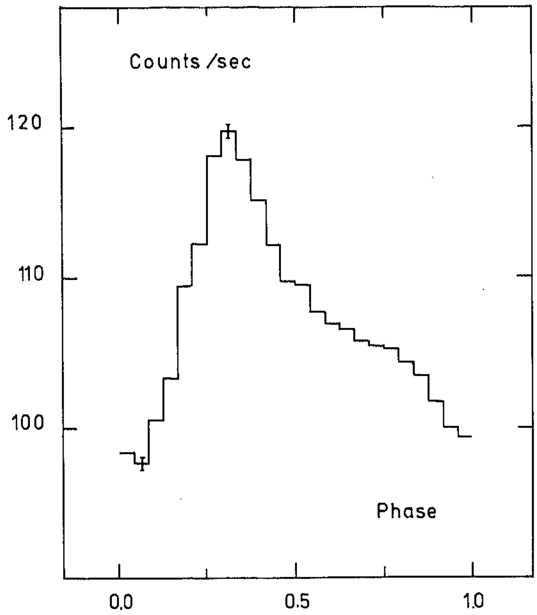

Fig. 3. Cen X-3 mean pulse shape during the month of observations, derived by averaging separate light curves produced for each binary cycle. Count rates are without background subtraction. Typical 1σ error bar is shown

inside these parts to make it possible to relate the mean spin-up to the mean L_x during the same stretch of time (see Chap. IV).

The pulsation period determinations and the results of the three least square fits are given in numerical form in Table 1.

b) Pulse Shape

We also examined the Cen X-3 pulse shape during the COS-B observation. For that purpose mean light curves were produced for each binary cycle, using the best fit value of the period as indicated above. An averaged pulse shape was then built by summing these curves phased relatively to each other. This mean pulse shape is shown in Fig. 3. It is a one peak curve with a sharp increase and a smooth decrease.

The uncertainties in the background level do not allow one to derive an accurate pulsed fraction, however, a good estimate will be about 40%, with an equivalent duty cycle (total pulsed power divided by peak value) of 0.25.

A significant fraction of the pulsed counts is present in the second part of the cycle (phase 0.5 – 1.0), corresponding to about 30% of the total pulsed power.

The pulse shape reported here is found to be similar to the Uhuru and the OSO-7 results (Ulmer et al., 1974; Ulmer, 1976). In particular there is no evidence of a double peak structure as reported for this source from other observations (Tuohy, 1976; Long et al., 1975). As the energy ranges were different for those experiments, no conclusion can be drawn about spectral or long term variability of the pulse structure.

Short term time variability of the pulsation curve during the month of observation has been investigated. The pulse shape was found to vary appreciably during the turn-on, showing an increasing pulsed fraction during the first orbits (orbit 1–2–3) and a wider peak in orbit 4–5–6. In the rest of the observation, no significant changes were found. However, a tendency to produce a weak

Table 1. The pulsation period of Cen X-3

Date[a] (days)	Time extension of interval (days)	Period (s)	1σ error (10^{-5} s)	Cycle	$-\dot{P}/P(10^{-4}\,\mathrm{yr}^{-1})$
0.15	2.52	4.834 650	0.5	1–2	
2.71	0.63	4.834 588	1.0	3	
5.75	0.57	4.834 544	1.7	4	10.5 ± 1.1
7.16	1.23	4.834 540	0.5	5	
9.35	1.34	4.834 509	0.4	6	
11.80	0.42	4.834 480	2.1	7	
13.51	0.73	4.834 454	1.5	8	8.1 ± 3.6
15.50	1.00	4.834 442	1.5	9a	
16.31	0.35	4.834 427	1.2	9b	
18.46	2.09	4.834 407	0.2	10–11	
19.93	1.68	4.834 380	0.2	11	5.6 ± 1.6
21.97	1.57	4.834 368	0.4	12	
25.82	0.64	4.834 348	1.3	14	

[a] 1.0 = 2442773.5 = December 27, 1975

second peak around phase 0.75 was noted in the beginning of the observation (orbit 1–9) as compared to the last orbits (10–14).

The features mentioned are reflected in the averaged pulse shapes presented in Fig. 2 for the three different parts of the observation.

IV. Discussion

Having presented the observational results concerning the pulsation of Cen X-3, we will now discuss these results in terms of the relation between the observed spin-up rate and the observed luminosity of the source, leading to constraints on the neutron star parameters and providing a test for neutron star models.

a) Theories on Spin-up

Only two theoretical models to our knowledge give quantitative predictions about the relation between L_x and $\dot{P}$: the simple model (Pringle and Rees, 1972; Lamb et al., 1973), in which it is assumed that the only torque working on the neutron star is that of the accreting matter, which transfers the angular momentum corresponding to a Keplerian orbit at the magnetospheric radius, and the model of Ghosh and Lamb (1978), who except for this accretion torque take into account the force of the matter in the disk on the magnetic field of the neutron star.

In the simple model it is possible to derive a straightforward relation between the spin-up rate and the X-ray luminosity.

The matter circulating in the disk at Kepler speed has a specific angular momentum $\ell = (GMr)^{1/2}$, where M is the mass of the neutron star and r the distance to its centre. At the Alfvèn radius, which we take to be

$$r_A = 3.2\,10^8 \mu_{30}^{4/7} \dot{M}_{17}^{-2/7} (M/M_\odot)^{-1/7} \quad (3) \quad \text{(Lamb 1977)}$$

where μ_{30} is the magnetic moment of the neutron star (units 10^{30} gausscm^2), and $\dot{M}_{17}$ is the accretion rate (units 10^{17} gs^{-1}), the matter transfers its angular momentum to the neutron star and its magnetosphere.

Estimating the X-ray luminosity produced in the accretion process to be equal to the gravitational energy, i.e., to about 10% of the rest mass of the accreting matter: $L_x = (GM/R)\dot{M}$, where R is the radius of the neutron star (Lamb et al., 1973), it is found that

$$-\dot{P}/P = 2\,10^{-5} f P L_{37}^{6/7}\,\mathrm{yr}^{-1} \quad (4)$$

with I_{45} the moment of inertia of the neutron star (units 10^{45} gcm^2). Where the factor containing the neutron star parameters is

$$f = 4\mu_{30}^{2/7} R_6^{6/7} I_{45}^{-1} (M/M_\odot)^{-3/7} \quad (5)$$

For both the simple model and the idea of Ghosh and Lamb, curves are given in Fig. 4 for several values of the neutron star parameters. As can be seen from the figure, for Cen X-3 these curves are nearly identical, though for somewhat different values of the neutron star parameters.

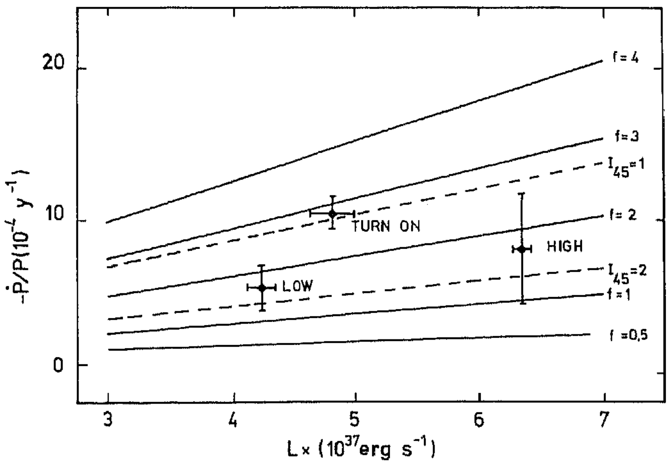

Fig. 4. Comparison of theoretical relations between $-\dot{P}/P$ and L_x with the results of the present observation of Cen X-3. Drawn lines are for simple unbraked accretion spin-up; the value of f is shown. Dashed lines represent the model of Ghosh and Lamb (1978) for neutron stars of $\mu_{30} = 1$, $R_6 = 1$, $M = 1.3M_\odot$ and I_{45} as shown

Braking Torques

As already noted by several authors, the simple model cannot explain all characteristics of the Cen X-3 pulsation behaviour: the spin-up is often lower than would be expected from the observed L_x, and also occasional spin-down episodes have been reported (Fabbiano and Schreier, 1977). Davidson and Ostriker (1973) pointed out that for relatively low accretion rates the Alfvèn radius could become larger than the corotation radius, causing matter to be ejected, thereby braking the rotation of the neutron star. In this way the spin period tends to keep an equilibrium value P_{eq}, at which the Alfvèn radius is equal to the corotation radius.

Adopting the Alfvèn radius of formula (3), this equilibrium period is calculated to be

$$P_{eq} = 3.1\mu_{30}^{6/7}\dot{M}_{17}^{-3/7}(M/M_{\odot})^{-5/7}\ \mathrm{s} \qquad (6)$$

Schreier (1977) further developed the braking idea, showing that reasonable amounts of ejected matter could explain the observed long term spin-up as well as occasional spin-down episodes. However, this model does not give a quantitative prediction for the behaviour of the source in the $L_x - P$ diagram during the time that the Alfvèn radius is large enough for braking to occur.

Long Term Spin-up

Savonije (1978) proposed an explanation for secular spin-up in X-ray binaries by showing that the mean accretion rate is expected to increase slowly because of the evolution of the primary star overflowing its Roche lobe. This causes the equilibrium period to decrease at a rate comparable to the spin-up rate observed in Cen X-3. Thus the counteracting forces of accretion and ejection of matter insure that the rotation period of the neutron star stays near P_{eq}, but this equilibrium point is slowly shifting for reasons of stellar evolution.

From the long term spin-up seen in Cen X-3, one can, taking the assumption of Savonije that this is due to a secular change in P_{eq}, deduce the change in accretion rate $\ddot{M}/\dot{M}$ necessary to explain this $\dot{P}_{eq}/P_{eq}$. The model for the evolution of the star then gives an indication for the mean $\dot{M}$ and thereby for the mean L_x at the present stage of evolution. This mean L_x is then the L_x at which the neutron star is spinning exactly at its equilibrium rotation period. For a higher L_x we expect unbraked accretion spin-up, when L_x gets lower some braking should start to occur.

For spin-up rates between 2.8 and $5.5_{10}-4$ yr^{-1} we find this critical L_x to be about $4_{10}37$ erg/s ($\dot{M} = 4.4_{10}17$ gs^{-1}). This number, derived from evolutionary calculations, should be considered as a good order of magnitude estimate, not as an exact value (Savonije, 1978).

In the next two paragraphs, the theoretical ideas described above will be compared to the results of the present observation.

b) Long Term Pulsation Period Change

The most striking feature of Fig. 1 is the high mean spin-up rate between the Ariel V and COS-B observations $(5.52 \pm 0.09)_{10}-4$ yr^{-1}, as compared to the one determined between Uhuru and Ariel V, $(3.23 \pm 0.04)_{10}-4$ yr^{-1} (Fig. 1). Fortunately, during the year 1975 the source was well monitored by the Ariel V All Sky Monitor (ASM) (Holt et al., 1978). so that the resulting mean luminosity observed can be fully checked against the observed spin-up rate during this period.

Assuming the simple model, we can rewrite formula (4) as:

$$L_{37} = 3.0_{10}5 f^{-7/6}\{(-\dot{P}/P)/yr^{-1}\}^{7/6} P^{-7/6} \qquad (7)$$

where f can be assumed to be 1.68 ± 0.74 for Cen X-3 (see next paragraph). This luminosity is actually a lower limit since braking torques are known to occur and to reduce the transmitted angular momentum and the observed long term spin-up rate.

For the measured slope in Fig. 1 between Ariel V and COS-B observations, the mean luminosity required for the source is then at least $L_x = (4.2 \pm 1.6)_{10}37$ erg/s. This is significantly higher than the mean luminosity observed by Ariel V during this interval. In fact, from the overall light curve reported (Holt et al., 1978) the mean flux is about 0.12 ph cm^{-2} s^{-1}, corresponding to a luminosity of $L_x = 1.87 \pm 0.25_{10}37$ erg/s, as deduced from a calibration on the Crab source (Kaluzienski, 1976). Both luminosities quoted are for a distance of 8 kpc.

This clearly shows, that the intrinsic luminosity of the source is affected by absorption during part of this stretch of data. It is stressed that this conclusion is independent of the distance assumed for the source since any correction to this distance will be reflected in the f value deduced from the source flux seen by COS-B. As during 20% of the time of the ASM observation the source can be considered to be in a low state compatible with the eclipse level (Holt et al., 1978), there is a strong indication that the low periods of the source correspond to periods of high accretion rate with high spin-up rate, and that the low luminosity at that time is caused by absorption. (See also next paragraph for the spin-up during the turn-on.)

Unfortunately the same coverage of the source flux is not available during the Uhuru-Ariel V observations interval, where the mean spin-up rate is found to be appreciably lower $(3.23 \pm 0.04_{10}-4$ yr$^{-1})$. Since the braking torques are expected to be efficient at luminosities lower than $4_{10}37$ erg/s, such a change could be explained by a gradual increase in the accretion rate from Uhuru to COS-B observations. This is compatible with both the larger luminosity found in the COS-B observation, and the strong braking effect seen by Fabbiano and Schreier (1977).

c) Short Term Pulsation Period Variation

Turning to the detailed pulsation period behaviour during the month of observations (Fig. 2), the first feature to remark is the high mean spin-up of about $_{10}-3$ yr^{-1}. Assuming that the angular momentum required for this spin-up is transferred to the neutron star by accreting matter, taking $L_x = 0.1c^2\dot{M} = 4_{10}37$ erg/s and the moment of inertia of the neutron star $I = {}_{10}45$ gcm^2, the specific angular momentum of the matter is calculated to be $9.3_{10}16$ cm^{2}s^{-1}g^{-1}, in good accordance with the specific angular momentum expected in case of disk accretion (Petterson, 1978).

From the existence of a disk in Cen X-3 we may not conclude, however, what the mode of mass transfer is, because at accretion rates of this magnitude the matter has a specific angular momentum high enough to form a disk, not only if the mass transfer is by Roche lobe overflow, but also if it is by stellar wind (Paper 1).

In Paper 1 it was concluded from the luminosity behaviour of the source that the COS-B observation of Cen X-3 essentially consists of three parts:

a) the turn on, during which the absorption by circumstellar matter is high and decreases quickly,

b) the high luminosity orbits, where absorption is unimportant, but the accretion rate high, and

c) the low luminosity orbits, which show a more or less normal accretion rate together with low absorption.

The mean $\dot{P}$ and also the pulse shape in each of these three parts of the observation confirm the general picture given above and lead to the interesting possibility of comparing these data to predictions by theories on spin-up.

The spin-up during the turn-on is not significantly different from that during the high orbits, confirming the assertion that the accretion rate during the turn-on is high and that the low L_x there is caused by absorption. This is also confirmed by the relatively flat pulse shape during the turn-on, attributed to scattering of the X-rays in the absorbing circumstellar matter. During the low luminosity orbits $-\dot{P}/P$ is significantly lower than before, which shows that accretion was really less at that time. Because the high and low orbits show little absorption, these two points can be compared to the theoretical predictions of the correlation between $\dot{P}$ and L_x (Fig. 4). It is seen that both the high and the low luminosity point are compatible with the simple spin-up model (drawn lines).

The factor f containing the neutron star parameters is determined to be 1.68 ± 0.74 for the high luminosity point and 1.64 ± 0.47 for the low luminosity point. These values are not significantly different, so there is no evidence from these data of braking occurring at luminosities above $L_x = 4.2_{10}37$ erg/s, in accordance with the suggestion from evolutionary arguments above. The mean value of f is 1.65 ± 0.44.

Assuming the dependence of intrinsic luminosity on $\dot{P}$ to be given by the same relation (formula (4)) during the turn-on as during the high and low luminosity orbits, the unabsorbed L_x there can be calculated to be $(9.0 \pm 2.6)_{10}37$ erg/s.

Behind this determination of f lie the assumptions of the simple model (paragraph a), which could lead to an underestimate of f (Lamb, 1977), and the observational value of L_x, which could be influenced by the assumed distance (8 kpc) and spectral shape (Paper 1), as well as by a possible correction for beaming of the radiation (Henry and Schreier, 1977). It can be seen from Fig. 4, however, that f does not depend very sensitively on L_x; the dependence on $-\dot{P}/P$ is much more important, and this quantity is measured directly.

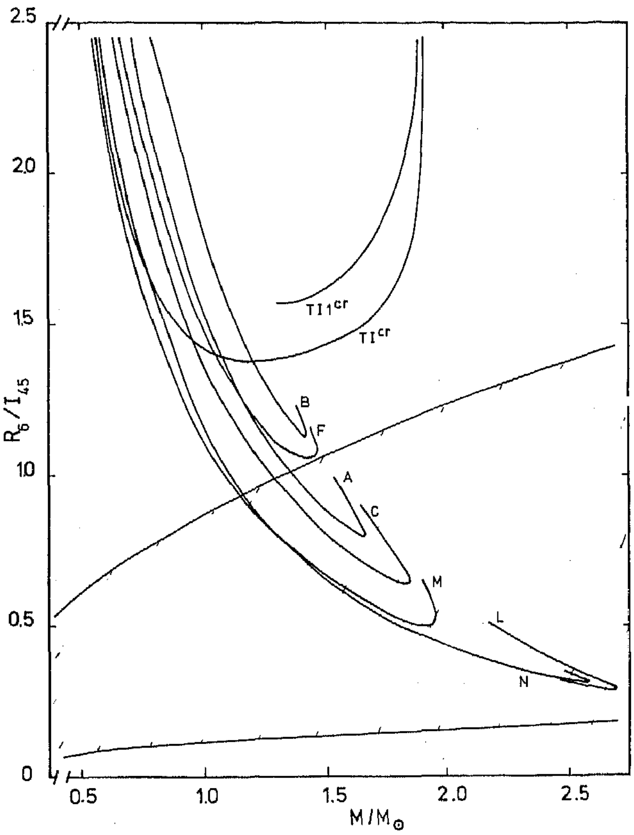

Fig. 5. The ratio R_6/I_{45} as a function of mass for different neutron star models. The hatched area represents the range on R_6/I_{45} allowed for Cen X-3 as derived from the present determination of f (1.7 ± 0.7). The models A–N were taken from Arnett and Bowers (1977) and span the full range of models published; for the models TI^{cr} and TI1^{cr} (Pandharipande et al., 1976) only the moment of inertia of the neutron star solid crust was taken into account

d) Neutron Star Parameters

Having shown that the present observation is consistent with the theoretical picture sketched in paragraph a), we now proceed, within this theoretical framework, to take a closer look at the neutron star itself.

It can be seen from expression (5) that the factor f appearing in the formula for classical accretion spin-up is only weakly dependent on μ. For radiopulsars, Ruderman (1972) derives a range of magnetic moments of $\mu_{30} = (0.26 - 4.4) I_{45}^{1/2}$ from observations of spin-down by assuming the rotational energy loss of the pulsar to be equal to one caused by radiation of a nonaligned rotating magnetic dipole in vacuum. Assuming the μ of Cen X-3 to be somewhere in this range, and using the present determination of $f = 1.68 \pm 0.74$ (excluding the low luminosity orbits to be sure no braking is affecting the value of f), it is found, that

$$R_6/I_{45} = (0.11 - 0.87)(M/M_\odot)^{1/2} \tag{8}$$

This result is compared for a large range of possible masses to predictions which can be made from theoretical models of neutron stars in Fig. 5. The models A–N appear with the same designations in the paper by Arnett and Bowers (1977). Not all models given there are included in the picture to avoid cluttering, but the full range of R_6/I_{45} values is covered by the curves shown. The models TI and TI1 were taken from Pandharipande et al. (1976); these are models with a tensor interaction equation of state in which a solid crust is believed to enclose a liquid interior. We assumed the crust to be totally decoupled from the interior and took only the moment of inertia of the former to compute R_6/I_{45}.

The assumption of total decoupling clearly bends the curves for these models out of the range allowed by the present observation, while without this assumption the tensor interaction model (curve M) is quite within this range. Also the model B (Pandharipande, 1971), F (Arponen, 1972) and G (Canuto and Chitre, 1974, not shown in the figure), are made improbable by this observation. It is remarkable that following the classification by Arnett and Bowers (1977) only the models based on the stiffer equations of state can account for the observed ratio of R and I.

Under the assumption that a neutron star has a structure which is somewhere in the range of models proposed to this date, it is clear from Fig. 5 that we can, independent from other determinations, derive a lower limit to the mass of the Cen X-3 neutron star of $1.1\ M_\odot$.

Another constraint on the neutron star parameters can be obtained from the assumption that Cen X-3 is spinning at the equilibrium period (formula (6)). The neutron star is expected to rotate at the period corresponding to the mean accretion rate $\bar{\dot{M}}$. A good order of magnitude estimate of this number was already given in paragraph a): $\overline{\dot{M}}_{17} = 4.4$. The range of masses of Cen X-3 from radial velocity curves and eclipse durations is often quoted in recent publications as $M = (0.6 - 1.8)\,M_{\odot}$ (Avni and Bahcall 1976, Joss and Rappaport 1976), but see also Lamb (1977).

Combining these data it is found, that the assumption $P = P_{eq}$ implies: $\mu_{30} = 2.3 - 5.7$, consistent with the range assumed for μ above.

V. Conclusion

Correlated $\dot{P} - L_x$ measurements of neutron stars in binary X-ray systems provide an important test of theories both on accretion and on neutron star structure.

The present observation provides a determination of the properties of an individual neutron star rather than of the class as a whole.

From the results emerges the picture of a neutron star heavier than 1.1 $M_{\odot}$, which is accelerating its rotation by accretion from a Keplerian disk, with no significant braking forces acting at least at luminosities over $4.2_{10}37$ erg/s. Sometimes the X-rays it emits are obscured by absorbing matter, but its accretion rate and thereby the intrinsic luminosity during these low states is even higher than otherwise, as is betrayed by its high spin-up in the December 1975 turn-on: there its calculated L_x was $\sim 9_{10}37$ erg/s.

We found some conditions constraining the possible equations of state governing the interior of this neutron star (the stiffer ones seem to be favored), but most possibilities are still admitted; future observations should make it possible further to tighten these constraints.

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