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The Accretion Picture of Cen X-3 as Inferred from One Month of Continuous X-ray Observations

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Summary. COS-B December 1975 X-ray observations of Cen X-3 include a turn-on of the source and a high state extending over the rest of the observation period during which a clear transition in intensity occurs. Using these data, we show that the accretion picture of Cen X-3 is only reconcilable with a stellar wind by taking the most extreme assumptions on the mass loss of the primary and the velocity of the wind. It is argued that the observed high X-ray luminosity together with the intensity behaviour of the source demonstrates the presence of an accretion disk, for which a radial flow time of ~ 15 days is derived.

Key words: X-ray binaries – accretion disks – stellar wind – COS-B

I. Introduction

Cen X-3 was the first X-ray source discovered to be a pulsator in a binary system (Giacconi et al., 1971; Schreier et al., 1972) and was associated some time later with an early-type star (Krzeminski, 1974). In spite of many further observations (Schreier et al., 1976; Swank et al., 1975; Pounds et al., 1975; Tuohy and Cruise, 1975), the mode of accretion in the case of this luminous X-ray binary is not yet well established; experimental evidence indicates the presence of a stellar wind as well as a disk (Schreier and Fabbiano, 1976; Fabbiano and Schreier, 1977), while it has been argued that from a theoretical point of view critical lobe overflow is necessary to explain the observed X-ray luminosity of the source (Conti, 1978; Petterson, 1978) and the existence of a disk (Petterson, 1978).

In this paper we report the data obtained with the X-ray detector onboard the ESA COS-B satellite during a one-month observation when the satellite was continuously pointed at Cen X-3, the duration of this observation allowing a complete description of an interesting transition in the source flux.

II. Observations

The X-ray detector of the COS-B satellite is a collimated proportional counter which has been fully described by Boella et al. (1974).

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The effective area is 80 cm^2 with a collimated field of view of 10° FWHM with a 1° flat top and an energy response between 2 and 12 keV with a maximum at 6 keV. The accuracy in the pointing direction is better than $0^\circ 5$. X-ray counts are accumulated during 25.4 s and transmitted every 102.4 s together with three other counting rates allowing the rejection of charged particles by both anti-coincidence and rise-time discrimination.

The satellite was continuously pointed at Cen X-3 from JD 2442771.0 to JD 2442801.5. At this time, the COS-B collimator also included other contaminating sources (mainly 4U 1145-61) which contribute for at most 3 counts/s to the total counting rate.

Figure 1 shows the behaviour of the source during the month of observation. Each 1024 s bin represents the average of 10 equally spaced 25.4 s measurements of the 2–12 keV intensity. The residual background has been subtracted from the data presented here via correlations similar to those used by Davidson (1974) for OAO-C. Gaps in the curve are mainly due to rejection of data because of severe contamination by charged particles. The typical error for one bin is 1–2 c/s, including both 1σ counting statistics and uncertainties in the background correction due to short-term variability. Residual counting rate in eclipses may be due to the contaminating sources quoted above.

a) Orbital Period

The dashed lines represent the limits of the eclipses computed from the zero-phase point and eclipse duration derived from Tuohy (1976) and Schreier et al. (1972). These predictions are evidently in general accordance with our data.

From full resolution data on three eclipses for which both entrance and exit were observed, we consistently determine the zero phase to be $\phi_0 = \text{JD } 2442787.177 \pm 0.003$ (heliocentric time) assuming symmetry of the eclipses around this point. (As absorption effects seem to affect mostly the entrance into the eclipse, this value may be somewhat too low.) Figure 2 shows the general behaviour of the orbital period of Cen X-3 including UHURU Ariel V and COS-B observations. The COS-B determination does not contradict the general acceleration of the binary period as reported by Fabbiano and Schreier (1977). There is an indication, however, of a somewhat slower period decrease.

b) Shape of the Lightcurve

The behaviour of the source at the beginning of the COS-B observation is quite similar to the transition from a low to a high state (turn on) reported by Schreier et al. (1976), which can be

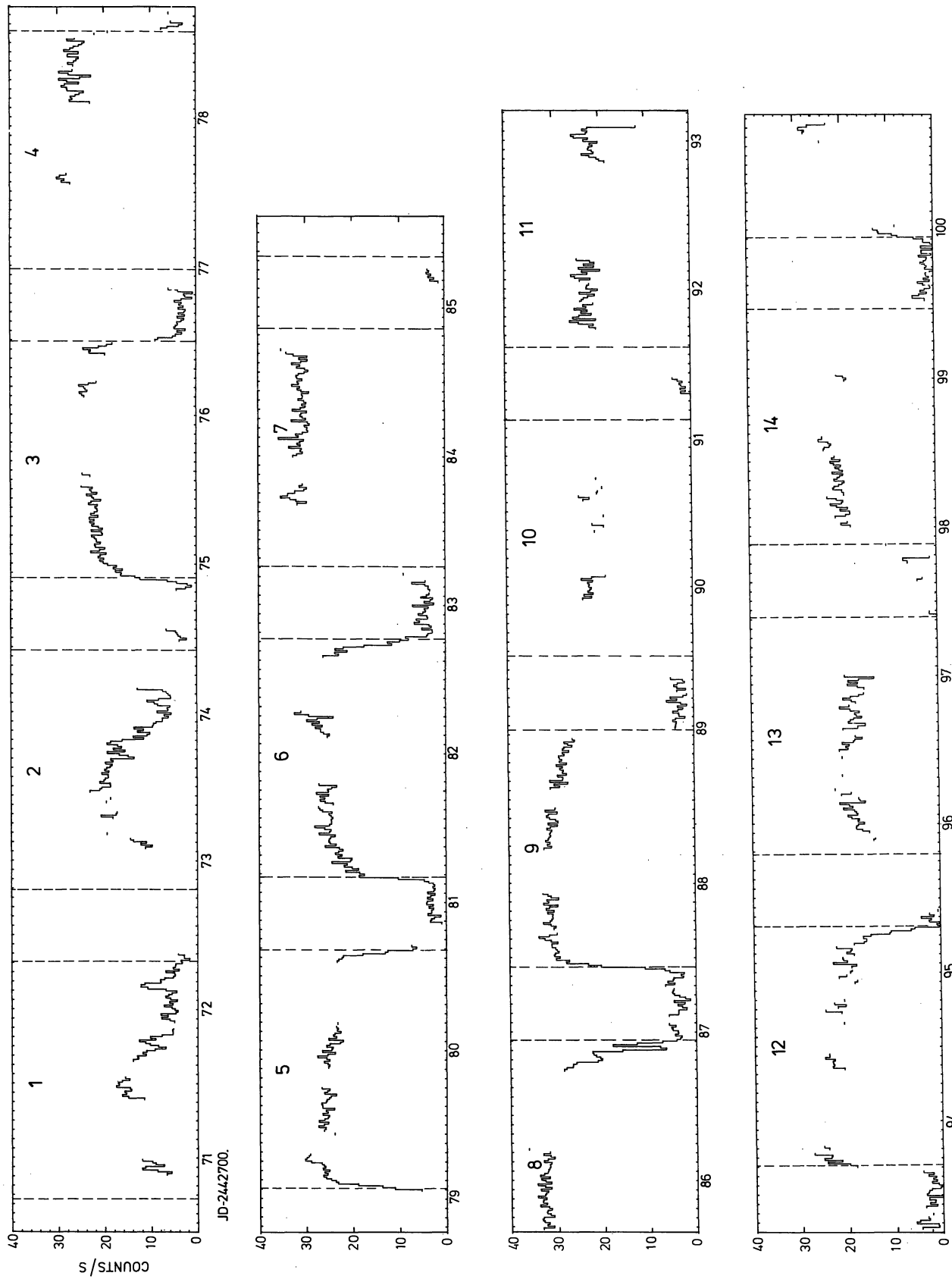


Fig. 1. The counting rate from Cen X-3 during 14 subsequent binary cycles. The dashed lines show predicted eclipse entrances and exits. The typical error in one 1024 s bin is 1–2 c/s. Data gaps are caused by contamination by charged particles. Note the turn-on behaviour in cycles 1–3 and the sudden decrease in counting rate from cycle 9 to 10

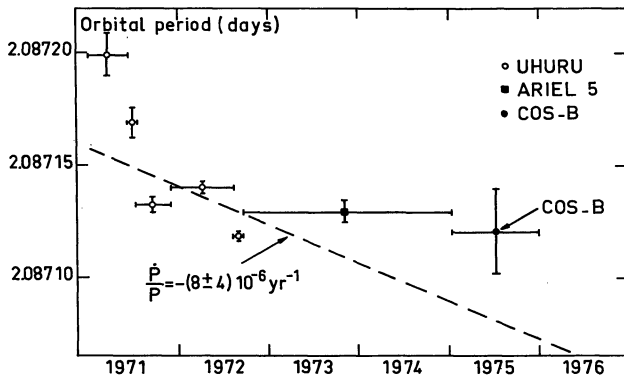


Fig. 2. The average heliocentric orbital period of Cen X-3. The COS-B point is determined from three eclipse center times. Other points are from Fabbiano and Schreier (1977). The dashed line represents the best linear period change from 1971 to 1974 as determined by Fabbiano and Schreier (1977)

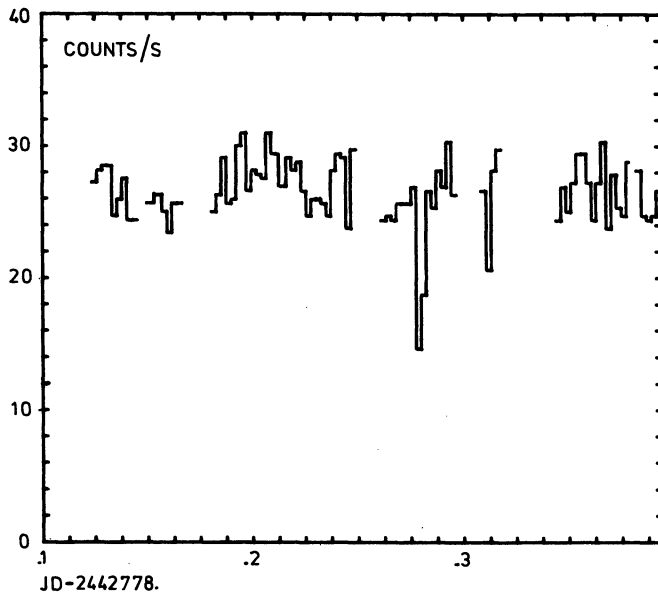


Fig. 3. The small but significant dip in cycle 4. The error in one 204.8 s bin is estimated to be ~ 4 c/s, mainly due to short term background variability

ascribed to a change in the absorption by the circumstellar gas. It seems that we see the last two binary cycles of this type of behaviour. The mid-phase spike structure is clearly visible, but in both cycles a certain asymmetry exists, intensity being lower in the second part of the lightcurve, after the mid-phase point.

In spite of the lack of spectral information from the detector, the similarity of this lightcurve with those of previous observations leads us to conclude that this kind of phase-dependent lowering in intensity is also due to absorption in the present observation. After cycle 2, there is a clear change in the shape of the lightcurve, cycle 3 being quite comparable to a standard square lightcurve. In all subsequent cycles, the uneclipsed part is quite flat, while absorption seems to affect only the part of the lightcurve nearest to the eclipses, 15% of the period at most.

In particular, there is no evidence in the present observation for large mid-phase absorption features like those seen by Ariel-5

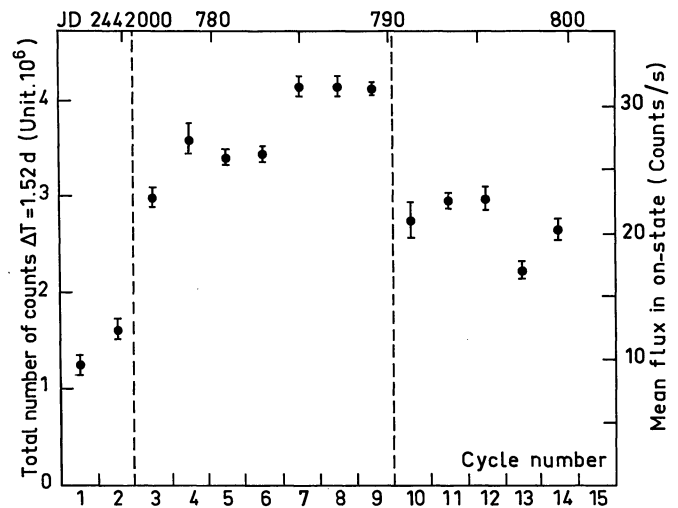


Fig. 4. The total number of counts received during the uneclipsed parts of each of the binary cycles. The error bars represent the estimated uncertainties caused by interpolation through data gaps. The 2-3 intensity transition is due to the turn on. For a discussion of the 9-10 intensity decrease, see text

(Pounds et al., 1975), nor for any mid-phase intensity cut-off as reported from Copernicus data (Tuohy and Cruise, 1975).

Surprisingly, the two dips already reported from 10% of the present data (Benett et al., 1976), are the most important features of that kind. Only one more significant dip has been found, in cycle 4 (see Fig. 3).

c) Mean Intensity Variations

Except for the intensity change due to the turn-on, the source clearly undergoes several more changes in its mean intensity level. In Fig. 4, we show the mean counting rate for the uneclipsed part of each of the binary cycles, determined by performing interpolation through the gaps in the observations. The source is seen at its highest intensity level (31 c/s) during the three cycles 7, 8, and 9. During the earlier cycles (3-6) and the later ones (10-14), the intensity remains quite constant, but at lower levels, while during the first two cycles the intensity is rather low, which can be ascribed to the high absorption during the turn-on. The transitions between the four intensity levels all occur within one day. It is interesting to note that the last two changes in intensity are quite comparable in time scale and form to the April 1975 Copernicus observation (Tuohy and Ilovaisky, private communication), where no change in hardness ratio is found, as well as to the March 1972 UHURU observation which cannot be fully explained by absorption (Schreier et al., 1976).

d) X-ray Luminosity

During the three high-intensity cycles the observed counting rate is consistent with an average value of 31 c/s. For the Crab source the relation between COS-B and UHURU counts is about 1 COS-B count = 10.8 UHURU counts, so that, in a first approximation assuming a spectrum for Cen X-3 identical to the Crab spectrum, an intensity of 335 UHURU counts is found for Cen X-3, much higher than the 200 c/s given in the UHURU catalog (Forman et al., 1977) as a maximum flux for this source but comparable with the counting rate seen by UHURU during one third of a binary

period in June 1971 (Gursky and Schreier, 1974). (These data were not included in the 4U catalog because of lack of accurate aspect.)

With more accurate spectral assumptions we compute the X-ray luminosity in the 2–12 keV energy band to be $6.3 \cdot 10^{37}$ erg/s, assuming a distance of 8 kpc (Krzeminski, 1974). In this computation we use the average spectral shape fitted by Swank et al. (1975) to an exponential curve: $\exp(-E/kT)$ with $kT=5.6$ keV, and we take the Crab as a calibration source for the detector. The high state spectrum given by Schreier et al. (1976) [$\exp(E_a/E - E/kT)$ with $kT=20$ keV and $E_a=2.0$ keV] will lead to a somewhat higher luminosity.

The maximum luminosity commonly observed by the UHURU satellite is $L_x=3.5 \cdot 10^{37}$ erg/s in the 2–10 keV energy band (corresponding to 200 c/s), which is lower by nearly a factor of two than the COS-B value, even if we take into account the difference in energy band and in spectral assumption which together could change the luminosity by 20% at most.

The present observation, then, is consistent with a high state of Cen X-3, at a higher luminosity than usually reported. In what follows, we argue that such a luminosity probably rules out the stellar wind as the only source of accreted matter in Cen X-3.

III. Discussion

a) The X-ray Luminosity and the Wind Accretion Model

As already noted by several authors (Lamers et al., 1976; Conti, 1978), the high luminosity of Cen X-3 is difficult to explain in terms of a stellar wind model.

The standard formula for the accretion rate in a stellar wind is:

$$\dot{M}_x = \varepsilon \dot{M}_* \quad (1a)$$

with the accretion efficiency:

$$\varepsilon = \frac{G^2 M_x^2}{a^2 v_{rel}^4} \quad (1b)$$

where \dot{M}_x is the accretion rate, \dot{M}_* is the mass loss of the primary star, M_x the mass of the compact star, a the orbital distance between the two stars and v_{rel} the velocity of the wind relative to the compact star near the compact star. It is clear, that the efficiency ε is highly dependent on the velocity of the wind, a low relative velocity being required to produce a high luminosity. In that case, we can no longer take v_{rel} to be equal to the radial wind velocity v_w (as in formula 1), but we have to introduce both the orbital motion of the neutron star and the rotation of the primary.

The full calculation of ε for an X-ray source in a stellar wind for any case of rotation of the primary star is given in Appendix 1. Using this efficiency factor, we can then write the X-ray luminosity as:

$$L_x = \eta L_* \frac{c}{v_T} \frac{(M_x/M_*)^2}{\left(\frac{v_T^2 a \psi^2(a)}{GM_*}\right)^{1/2} \left(\frac{v_T^2 a \psi^2(a)}{GM_*} + \left(1 - \frac{\lambda R_*^2}{a^2}\right)^2 \cdot \left(1 + \frac{M_x}{M_*}\right)\right)^{3/2}} \quad (2)$$

where:

ηc^2 is the conversion factor of rest mass to X-rays ($\eta \sim 0.1$ for neutron star),

M_* and M_x are the masses of the primary and the secondary respectively,
 L_* is the luminosity of the primary,
 R_* is the radius of the surface of the primary star just below the position of the X-ray source (substellar radius),
 a is the binary separation,
 v_T is the terminal velocity of the wind,
 $\psi(r)$ is the ratio at a distance r of the radial wind velocity v_w to v_T , and
 λ is the rotation parameter, the ratio of stellar to orbital angular velocity.

In this calculation we have used an upper limit for the mass loss of the primary star in the case of a purely radiation-driven stellar wind, which is reached when all the momentum of the radiated photons is transferred to the wind, which gives:

$$\dot{M}_* = \frac{L_*}{c v_T} \quad (3)$$

Following Lamers et al. (1976), we introduced a substellar radius instead of a mean lobe radius to describe the shape of the primary. This radius was computed from Pratt and Strittmatter (1976) who give a more detailed treatment of the equivalent Roche surface. In case of Cen X-3, the relation between substellar radius and rotation parameter is found to fit the quadratic relation $a/R_* = \alpha + \beta \lambda^2$ (with $\alpha=1.230$ and $\beta=8.02 \cdot 10^{-2}$).

Using a review of velocity profiles given in a recent article of Conti (1978), two different profiles deduced from models for purely radiation-driven winds were chosen. These two models can be considered as an upper limit to the velocity of the wind (Castor et al., 1975) and a lower limit (Abbot, 1977) respectively; the Barlow and Cohen (1976) profile was excluded because it is based upon only one star, P Cygni, which does not seem to be representative of the kind of OB stars commonly found in X-ray binaries. (See, e.g.: M. de Groot, 1971). In Fig. 5 the predicted luminosity for the source has been plotted as a function of the terminal velocity v_T . Curves are given for different values of the rotation parameter λ .

The terminal velocity of the wind has been shown to be related to the escape velocity at the surface of the optical star. The value of the ratio v_T/v_{esc} found by different authors varies from 2.8 (Lamers et al., 1976) to 3 or 4 (Snow and Morton, 1976), which leads in the case of Krzeminski's star to a terminal velocity of 2100–2900 km s⁻¹. More recent work by Abbot (1978), based upon the same set of Copernicus observations of 47 OB stars as Snow and Morton's, but using an escape velocity corrected for radiation pressure, leads to the linear relation $v_T=2.65 v_{esc} + 550$, which results in $v_T=2000$ km s⁻¹ for Krzeminski's star. We keep this value as the lower limit for v_T in the case of Cen X-3.

Figure 5 clearly shows the predominant influence of the wind profile on the luminosity of the X-ray source in the case of a close binary system as Cen X-3. For the range of possible values for v_T and most wind profiles assumed (i.e. between the extremes of the Abbot and CAK profiles), the X-ray luminosity predicted for Cen X-3 from a stellar wind accretion model will be several times lower than the one observed, even taking into account the rotational distortion of the primary.

The observed high luminosity can only result from a very slow (Abbot-type) wind, and will then depend significantly on the rotation parameter, requiring the primary star to be very near to corotation. In the Cen X-3 binary system, there are several arguments against corotation. For the primary to be in

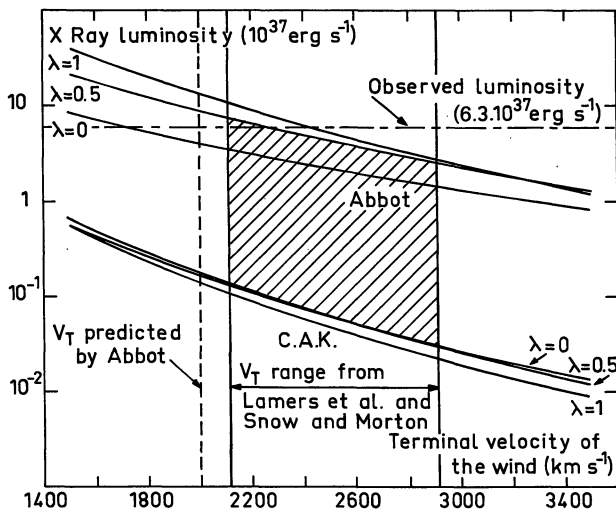


Fig. 5. The predicted X-ray luminosity for stellar wind accretion as a function of the terminal velocity v_T [see formula (2)], for $L_* = 6.8 \cdot 10^{38} \text{ erg s}^{-1}$, $M_x = 1 M_\odot$, $M_* = 18 M_\odot$, $a = 1.2 \cdot 10^{12} \text{ cm}$ and $\lambda = 1, 0.5$, and 0 , assuming the mass loss rate from the primary to have its maximum value. Curves are given for two different wind profiles [Abbott, D. C. (1977) and Castor et al. (1975)] which can be considered as limits for a radiatively driven wind. For the range of possible wind profiles and values of v_T (see text), the predicted X-ray luminosity (hatched area) mostly falls below the observed value

corotation, its equatorial velocity should be $\sim 350 \text{ km s}^{-1}$. From spectroscopic data, it seems that the observed value is well below 200 km s^{-1} (Conti, 1978), which is more in agreement with the $\sim 70 \text{ km s}^{-1}$ given as an average for an O6.5 III star (Lamers et al., 1976). At the same time, the asymmetry of the light curve during the first two cycles of our observation, due to more absorption before than after the eclipse, could be the manifestation of material kicked up from the tidal bulge, which again points in the direction of non-corotation.

Summarizing, it can be said that in the calculation of the X-ray luminosity predicted by the stellar wind model, all parameters have to be stretched towards extreme limits to explain the observed X-ray flux. The mass loss was taken to be at its theoretical maximum, the influence of the distortion of the primary on the stellar wind at the X-ray source was accounted for in a generous way, all possible profiles were considered, and still a very low terminal velocity together with a primary star near corotation are needed to explain the observed luminosity.

It seems reasonable therefore to state that wind accretion alone cannot explain the X-ray luminosity of Cen X-3 and that critical lobe overflow probably is important at least at times of high luminosity like observed by COS-B.

b) An Accretion Disk in Cen X-3

We wish to point out that during a high state of this source accretion necessarily takes place through a disk, the signature of such a disk being found here in the observed flux transitions.

It is well known that if the mass transfer occurs by critical lobe overflow of the primary, a disk is necessary to get rid of most of the angular momentum of the accreting gas relative to the compact object (Prendergast and Burbidge, 1968). It can also

be shown, using simple angular momentum considerations, that even if accretion is by stellar wind, there exists a lower limit to the X-ray luminosity of the source, above which a disk is always required, because the mass flux necessary to feed a source of this luminosity has too much angular momentum to fall directly onto the compact object (see Appendix 2).

For Cen X-3, this limit is $1 \cdot 10^{37} \text{ erg/s}$, so we can be sure that whatever the mass transfer mechanism, there will be a disk at least during the high state of the source. This fact implies that the high mass transfer rate required to explain the high luminosity during the cycles 7–9, must have taken place at an earlier time, because the matter needs some time to pass through the disk before being accreted (radial flowtime). During the time of high mass transfer, gas is also expected to be ejected from the primary star to the surroundings of the system. Following Schreier et al. (1976), we interpret the absorption in the early part of the observation (cycles 1 and 2) as being due to the presence of this gas and the clear transition between cycles 2 and 3 to an attenuation in its density. This attenuation is apparently caused by a decrease in the feeding of matter to the circumstellar environment, which we attribute to a change in the mass loss process. This same change will then have the effect of reducing the feeding of matter into the disk, which some time later is seen as the intensity transition between cycles 9 and 10, after the matter has passed through the disk. We may conclude, then, that the disk has a radial flowtime of $15 \pm 1 \text{ d}$, this being the time between the 2–3 and 9–10 transitions.

This value falls within the range of the predictions from theoretical disk models. Taking the radius of the disk to be 80% of the distance of the X-ray source to the first Lagrangian point, the model of Pringle and Rees (1972), in which the radial velocity is 1% of the Kepler velocity, predicts a radial flowtime of $\sim 7 \text{ d}$. The standard disk model, as described by Novikov and Thorne (1973), gives a radial flow time of $\sim 160 \text{ d}$ using the formula of McCray (1976).

IV. Conclusion

In the present observation of Cen X-3 the observed maximum luminosity strongly supports the idea that accretion cannot take place through a stellar wind only but rather through a more efficient way of mass loss of the primary such as a lobe overflow.

A new picture of the accretion process in Cen X-3 involving lobe overflow of the primary is quite promising in the light of recent theoretical predictions made by Savonije (1978) and Ziolkovski (1976). For a Cen X-3 type system, these authors find a period of over 10^4 yr during which the source can be powered by Roche lobe overflow without being buried by an excessive rate of accreted matter.

In that case the disk suggested here will be a normal consequence of this accretion process.

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Appendix 1

The Influence of Tangential Velocities on the Accretion Rate from a Stellar Wind

In introducing the effects of tangential movements in the derivation of the accretion rate from a stellar wind, one should take care not just to replace the radial wind velocity v_w by the relative velocity of the wind and the compact object v_{rel} .

In the formula for the accretion rate $\dot{M}_x = \pi r_a^2 \rho v_{rel}$ (Davidson and Ostriker, 1973), one has to substitute the expression for the accretion radius $r_a = 2GM_x/v_{rel}^2$ which uses the relative velocity, but the density of the gas at the orbit of the X-ray source should still be computed with the radial wind velocity:

$$\rho = \frac{\dot{M}_*}{4\pi a^2} \cdot \frac{1}{v_w} \quad (\text{mass conservation}). \quad (1)$$

The error introduced by taking v_{rel} instead of v_w can be important when a slow wind is assumed. (For Cen X-3, assuming the Abbot profile the correction factor is around 0.7).

Substituting, we find for the accretion rate efficiency:

$$\varepsilon = \frac{\dot{M}_x}{\dot{M}_*} = \left(\frac{GM_x}{a}\right)^2 \cdot \frac{1}{v_w v_{rel}^3}. \quad (2)$$

In this formula $v_{rel} = (v_w^2 + v_{tang}^2)^{1/2}$, where the tangential velocity v_{tang} is composed of the tangential movements of compact object and wind:

$$v_{tang}^2 = \frac{G(M_x + M_*)}{a} \left(1 - \lambda \frac{R_*^2}{a^2}\right)^2 \quad (3)$$

λ being the rotation parameter (ratio of stellar to orbital angular velocity). If we also express v_w at distance r from the star in terms of the terminal wind velocity v_T : $v_w^2 = v_T^2 \psi(r)$ the result is:

$$\varepsilon = \frac{(M_x/M_*)^2}{\left(\frac{v_T^2 a \psi^2(a)}{GM_*}\right)^{1/2} \left[\frac{v_T^2 a \psi^2(a)}{GM_*} + \left(1 + \frac{M_x}{M_*}\right) \left(1 - \lambda \frac{R_*^2}{a^2}\right)^2\right]^{3/2}} \quad (4)$$

Appendix 2

The Criterion for the Formation of a Disk in a Wind

Following Petterson (1978), we take the criterion for the formation of an accretion disk in a wind to be

$$J > Q \quad (1)$$

J being the mean specific angular momentum of the accreted wind matter and Q the specific angular momentum in the lowest stable orbit around the compact star.

$$J = \frac{1}{2} \Omega r_a^2, \quad \text{where } \Omega = 2\pi/P \quad (2)$$

is the orbital velocity, P is the binary period.

We compute the accretion radius r_a directly from the X-ray luminosity L_x using the standard formulae:

$$\dot{M}_x = \dot{M}_* \frac{\pi r_a^2}{4\pi a^2}, \quad \text{and } L_x = \eta \dot{M}_* c^2. \quad (3a, b)$$

where a is the distance between the centers of mass, \dot{M}_* the mass loss of the primary, \dot{M}_x the accretion rate of the compact star and η the efficiency factor, ~ 0.1 for a neutron star.

Using (3a, b) in (2), the expression for J becomes:

$$J = (4\pi a^2/P) \cdot (L_x/\dot{M}_* c^2) \cdot (1/\eta) \quad (4)$$

With (1), we find as a disk criterion:

$$L_x > Q \eta c^2 \cdot \left(\frac{P}{4\pi a^2}\right) \cdot \dot{M}_*. \quad (5)$$

The maximum value for \dot{M}_* is reached when the entire momentum of the photons emitted by the star: L_*/c is transferred to the wind, which gives:

$$\dot{M}_* \leq L_*/c v_T \quad (6)$$

where L_* is the luminosity of the primary and v_T the terminal velocity of the wind (i.e. at several stellar radii from the surface). (For this maximum mass loss, with $v_T = 2000 \text{ km s}^{-1}$ and a L_x of $6.3 \cdot 10^{37} \text{ erg/s}$, the value of J for Cen X-3 is $6.2 \cdot 10^{17} \text{ cm}^2 \text{ s}^{-1}$.)

If we take the radius of the lowest stable orbit around a magnetic neutron star to be equal to the Alfvén radius, Q will be in the range:

$$Q = (10-30) \frac{GM_x}{c}. \quad (7)$$

(For Cen X-3 this critical angular momentum is $Q \sim 9 \cdot 10^{16} \text{ cm}^2 \text{ s}^{-1}$, a factor 7 lower than the corresponding value of J .) Substituting (8) and (9) into expression (6), we find for the critical luminosity above which a disk is required:

$$\left(\frac{L_{x,crit}}{\text{erg s}^{-1}}\right) = (0.45-1.4) \cdot 10^{36} \cdot \left(\frac{P}{1d}\right) \left(\frac{\eta}{0.1}\right) \left(\frac{a}{10^{12} \text{ cm}}\right)^{-2} \left(\frac{M_x}{M_\odot}\right) \left(\frac{v_T}{2000 \text{ km s}^{-1}}\right)^{-1} \left(\frac{L_*}{10^{38} \text{ erg s}^{-1}}\right). \quad (8)$$

For Cen X-3 this critical luminosity is $L_x = (0.43-1.38) \cdot 10^{37} \text{ erg s}^{-1}$

We want to stress that no assumptions about the wind velocity profile or the radius of the primary are made in this calculation. [The above derivation is strictly valid only when tangential velocities are small compared to the radial wind velocity (see Appendix 1). Corrections for this are calculated to be small for reasonable velocity profile parameters: less than a factor 1.3.]

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Note added in proofs: Better accuracy in the zero-orbital phase determination was obtained by analysing high time resolution data on pulsation period (to be published). The derived new value is $\varphi_0 = 2442787.175 \pm 0.001$