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THE CHANGE IN WIND VELOCITY DURING A CENTAURUS X-3 TRANSITION

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ABSTRACT

A neutron star orbiting a stellar-wind star can be used as a probe of wind density and velocity. It is argued that Cen X-3 accretes mass from a stellar wind and that the model previously proposed by the author for supersonic accretion is applicable to Cen X-3. Combining X-ray data of one transition from low to high state, a previous suggestion that this type of transition is due to a decrease in the density of the stellar wind, and the model, allows one to deduce the variation of density and velocity in the stellar wind during the transition. It is found that the velocity decreases as the density decreases. This correlation between the stellar-wind density and velocity implies that the stellar-wind mass loss decreases during the transition. The result is discussed with respect to the mechanism for the acceleration of the wind.

Subject headings: stars: accretion — stars: winds — X-rays: binaries

I. INTRODUCTION

A neutron star orbiting a star with a stellar wind accretes gas from the wind to generate X-rays, which must then propagate through the accreting gas and the stellar wind in order to be observed. Thus a neutron star in a wind is potentially a powerful probe of the wind. The X-ray generated luminosity L_x is related to the unperturbed velocity V and density n by nV^{-3} (Davidson and Ostriker 1973). In order to have other equations relating the wind density and velocity to observable quantities, a theory of supersonic accretion from a stellar wind was developed by Carlberg (1978). The angular structure of the accretion column trailing the neutron star was derived to permit an estimate of the optical depth up the column to be made. X-rays produced at the surface of the neutron star are attenuated when the accretion column is in the line of sight. The depth and the character of the resulting dip in X-ray intensity are related to the physical parameters characterizing the neutron star and the wind. The X-ray observations of Cen X-3 made by Pounds *et al.* (1975) show the expected dips so clearly that the density and velocity of the stellar wind can be determined during the transition from X-ray low to high state.

II. THE MASS-LOSS MECHANISM OF THE PRIMARY

The theory of supersonic accretion given in Carlberg (1978) requires that a neutron star be immersed in a supersonic wind. The star associated with Cen X-3, Krzeminski's star, is a 14th magnitude O giant (Osmer, Hiltner, and Whelan 1975), which should have a stellar wind (Hutchings 1976). The mass transfer from the KRZ star to the Cen X-3 neutron star was originally proposed to be via a stellar wind (see Schreier, Swartz, and Giacconi 1976), but the high X-ray luminosity of Cen X-3 with an apparently weak stellar wind leads to some uncertainty. In fact, Peterson (1978), Lamers, van den Heuvel, and Peterson (1976), and Conti (1978) claim that the mode of mass transfer in the Cen X-3 KRZ star system may be Roche-lobe overflow. Their arguments are based on the relationship between the accretion rate from a stellar wind and the wind density and velocity at the orbital radius of the neutron star.

The accretion rate onto the neutron star, other than an accretion efficiency factor of order one, is

$$dM_x/dt = n_o V_r \pi R_A^2 . \tag{1}$$

The relative velocity V_r is defined by $V_r^2 = V_o^2 + V_W^2$, where V_o is the orbital velocity of the neutron star and V_W is the radial velocity of the wind. The orbital velocity V_o is measured with respect to the wind, i.e., $V_o = 2\pi a/T - V_{\rm rot} r_*/a$, where a is the orbital radius, T is the orbital period, and $V_{\rm rot}$ is the rotational velocity of the stellar surface of radius r_*. The accretion radius R_A is $2GM_x/V_r^2$. The density of the stellar wind is simply $dM/dt/(4\pi a^2 V_W)$, where dM/dt is the mass-loss rate from the star in a spherically symmetric wind. The resulting luminosity of the X-ray source will be the accretion rate times GM_x/R_x, M_x and R_x being the mass and radius, respectively, of the neutron star.

The luminosity equation can be solved to isolate the velocities,

$$\begin{aligned}(V_o^2 + V_W^2)^{3/2} V_W &= \frac{G^3 M_x^3}{L_x R_x} \frac{dM/dt}{a^2} \\ &= (620\ \mathrm{km\ s^{-1}})^4 m^3 (R_x/10\ \mathrm{km}) L_{37}^{-1} \dot{m}_6 a_{12}^{-2} , \end{aligned} \tag{2}$$

where $m = M_x/M_\odot$, $L_{37} = L/10^{37}$ ergs s^{-1}, $\dot{m}_6 = dM/dt/10^{-6}\ M_\odot$ yr^{-1}, and a_{12} is the orbital radius in units of 10^{12} cm. The values suggested by Conti for the Cen X-3 KRZ star system are $m = 1.5$, $\dot{m}_6 = 0.1$, $L_{37} = 5.7$, and $a_{12} = 1.3$. To evaluate a minimum wind velocity, we take V_o to be the full orbital velocity of 415 km s^{-1}, giving $V_w = 78$ km s^{-1}. This minimum wind velocity is higher than the value Conti found by the ratio V_r/V_W, i.e., his equation (8) is correct only if $V_r = V_W$, which for Cen X-3 requires a stellar rotational velocity of 540 km s^{-1}. The very low wind velocity derived by him was taken to imply that accretion from a supersonic wind was unable to supply sufficient mass to the neutron star at velocities typical of stellar winds.

If different values for the parameters are chosen, the implied wind velocity can be brought up considerably. Hutchings *et al.* (1978) have obtained spectra and X-ray observations of the KRZ star during an X-ray high. They find that the primary has spectral indicators characteristic of a mild stellar wind of 5×10^{-6} $M_\odot$ yr^{-1}. The orbital solution requires a mass of close to 1 $M_\odot$ for the neutron star. Using these values in equation (2) gives a minimum wind velocity of 420 km s^{-1}.

The intent of the above discussion is to show that current data are consistent with the hypothesis that Cen X-3 accretes from a stellar wind. The following argument only depends on the source being immersed in a supersonic wind, which need not be spherically symmetric.

III. THE X-RAY DATA AND INTERPRETATION

a) The Data

Pounds *et al.* (1975) have observed a transition from X-ray low to high state for Cen X-3 (1974 November 10–27), where dips in the X-ray intensity are seen every orbital cycle near phase 0.625. Their X-ray light curve in the high-energy channel has the following characteristics: (1) the maximum intensity of each cycle of the 2.1 day period is increasing, becoming nearly fully on after eight cycles; (2) midphase dips are visible from cycle 2 on; (3) initially, the dips are very deep, with optical depth of about 1–2; (4) the dips have a double minimum in cycles 5 and 6; (5) as the maximum intensity rises, the attenuation in the dips diminishes, and only a single minimum appears in cycles 7 and 8. Schreier, Swartz, and Giacconi (1976) have also obtained observations of a turnon event (1972, July 19–August 1). Although midphase dips do seem to be present in their data, the dips were not so clearly defined. Features common to the two events include a narrow spike in the intensity as the source first turns on (cycle 3 similar to July 23), midphase dips (cycles 5 and 6 similar to July 25), and decreasing attenuation as the turnon proceeds (cycle 8 similar to July 31).

The double minimum in the dips has been ascribed by Jackson (1975) to the scattering provided by the density enhancement on the two sides of an accretion column. The changing depth of the dips was attributed to the decreasing density in the wind. Schreier *et al.* (1976) have ascribed the general increase in intensity during the turnon to a gradually dropping wind density, which removes the smothering blanket of bound-free absorption. This model has been refined by Hatchett and McCray (1977).

b) The Model

Carlberg (1978) described the supersonic accretion process and the accretion column which trails the neutron star. The model describes the structure of the accretion column in the radial and axial directions. By requiring the internal pressure of the column to balance the incoming momentum flux, the semi-angular width of the accretion column was found to be

$$\theta = 2.7°(T_C/10^6 \text{ K})V_8^{-2}, \tag{3}$$

where V_8 is $V_r/10^8$ cm s^{-1}. Setting the time for photoionization heating in the column at less than or equal to the time to fall down the column restricts the temperature to

$$T_C/10^6 \text{ K} \leq 1.9 n_{11}{}^{4/15} V_8{}^{4/15}, \tag{4}$$

where n_{11} is the particle density of the unperturbed stellar wind in units of 10^{11} cm^{-3}. The temperature would be expected to be near equality. Jackson quotes an angle θ of 20° and derives relative velocities of 375–620 km s^{-1} from the Pounds *et al.* (1975) data. Taking the fully-on density and velocity as $n_{11} = 1$ and $V_8 = 0.6$ (see below), equations (3) and (4) give an angle $\theta = 13°$. Thus the theory (within a factor of 2 error) indicates that the velocity and density chosen are consistent with the independently measured column angles.

Two relations describing the accretion column are of primary interest here. The optical depth due to electron scattering up the center of the column is

$$\tau_C \geq 2.2 n_{11}{}^{-8/15} V_8{}^{52/15}. \tag{5}$$

As with equation (4) above this is expected to be near equality. The density and velocity at which the optical depth up the sheath of the column exceeds the optical depth up the center of the accretion column ($\tau_S > \tau_C$) are related by

$$n_{11} V_8{}^{-2} > 3.5\,. \tag{6}$$

When $\tau_S > \tau_C$ we expect the dips to have a double minimum.

c) The Assumptions of the Model

The gas flowing at relative velocities in excess of 500 km s^{-1} is highly supersonic if the stellar wind is at a temperature of less than 4×10^5 K. But calculations by Hatchett and McCray (1977) indicate that significant X-ray heating occurs in the wind near the neutron star, reducing the Mach number to as low as 1.7. This alters some of the assumptions under which the original model was derived, but for the parameters of Cen X-3 thermal corrections would be fairly small. A low Mach number would have only a small effect on the luminosity and the optical depth up the center of the column. The sheath optical depth would be most affected, since it is determined by the distance at which the sheath blends into the flow. Only for Mach numbers less than 2 does the sheath start to be greatly altered, moving the $\tau_S > \tau_C$ line to slightly higher densities. The estimates made above are assumed to be adequate.

The only opacity source considered is electron scattering. The data of Pounds *et al.* (1975) indicate that the X-ray spectrum has a greater low-energy cutoff in the dip than at cycle maximum. This implies a photoionization contribution to the opacity. However, the high-energy channel (2.4–19.8 keV), which has the longest data segment, would be least affected by photoionization absorption, and most representative of pure electron scattering. The high-energy light curve is used as the basis of the discussion below. The model can be used to estimate the expected ratio of the low-energy absorption in the column to that in the sheath. For the parameters of Cen X-3 the column temperature is $1\text{–}2 \times 10^6$ K. The sheath optical depth is dominated by the gas farthest from the X-ray source, the postshock temperature in the sheath being $3 \times 10^6(r/10^{11}\ \text{cm})^{-1}$. For termination distances r of approximately $1\text{–}2 \times 10^{11}$ cm, temperatures very close to those predicted for the column are found. Thus, within this simple model for this particular case, it is not clear whether the column or the sheath will have the greatest low-energy absorption. The data of Pounds *et al.* (1975) suggest that the sheath is slightly cooler, since the double-dip minima are slightly deeper at low energy, whereas the secondary maxima have roughly the same attenuation at low and at high energies.

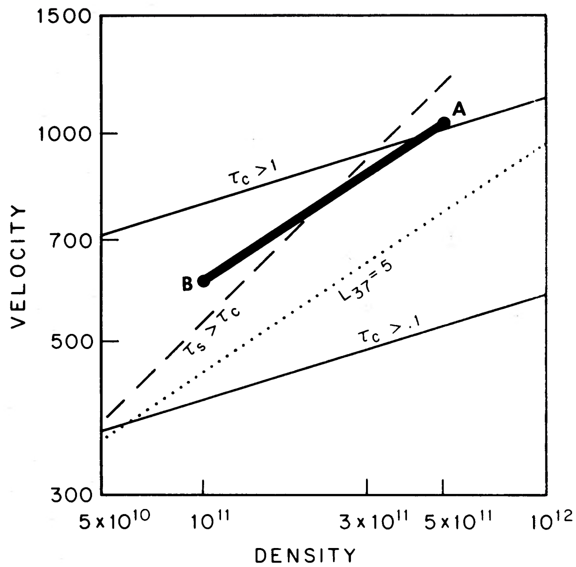

FIG. 1.—Density and velocity for Cen X-3. During the turn-on the density and velocity drop from point A to point B. The trajectory was deduced by comparing the X-ray light curve with the regions in the diagram. The lines indicated are: column optical depths of $\tau_C > 1$ and $\tau_C > 0.1$; the region of double minima, $\tau_S > \tau_C$; and constant luminosity, $L_x = 5 \times 10^{37}$ ergs s^{-1} for $m = 1$.

d) Interpretation of the Data

Figure 1 schematically shows the deduced trajectory of the stellar-wind density and velocity during the X-ray turnon observed by Pounds *et al.* (1975). At point A the source is in the X-ray low-intensity state and at B the high-intensity state. As discussed above, this turnon appears to be very similar to the one observed by Schreier *et al.* (1975). They propose that the source is initially smothered in the stellar wind at a local density of about 5×10^{11} cm^{-3}. The wind density gradually drops to 10^{11} cm^{-3}, at which time the source is fully on. This interpretation given by Schreier *et al.* (1975) is consistent with the interpretation given below of the data of Pounds *et al.* (1975). Therefore, it is assumed that these turnons are essentially the same, the only difference being the greater visibility of the dips in the data of Pounds *et al.* (1975).

The Pounds *et al.* (1975) X-ray data indicate that as the source first turns on the dips have a central attenuation corresponding to an electron scattering optical depth of about 1.7. This places point A just above the $\tau_C > 1$ line, at $n_{11} = 5$ and $V_8 = 1$. Note that point A has $\tau_S > \tau_C$ which produces the double minimum as observed. As the density drops, the velocity must move below the $\tau_C > 1$ line in order that the fractional depth of the dips may decrease. As this occurs the density-velocity trajectory crosses the $\tau_S > \tau_C$ line, so that the dips become single. At the assumed final density and velocity of $n_{11} = 1$ and $V_8 = 0.6$, the luminosity is 5×10^{37} ergs s^{-1} for $m = 1.3$. The initial luminosity was 5.4×10^{37} ergs s^{-1}. The trajectory is such that the change in intrinsic luminosity is fairly small, the drop in density compensating for the drop in wind velocity.

The relative wind velocity V_8 has dropped from about 1 to 0.6, so the wind velocity V_8 has dropped from about 0.8 to 0.5, the values depending on the stellar rotation. Thus the mass loss via the wind has dropped by a factor of 5–10 during the transition, if the wind is spherically symmetric.

The drop in wind velocity found should result in the midphase dip becoming wider (by eq. [3]) and occurring at slightly later phases. For an orbital velocity of 415 km s^{-1}, the midpoint should have moved back by about 0.08 of an orbital period. But since the dips are only clearly present in cycles 5–8 of the Pounds *et al.* (1975) data, the phase shift in the midpoint of the dip would be less than 0.08. Pounds *et al.* (1975) find no significant phase shift during the transition. The expected increase of the width of the dip may be marginally present in the Pounds *et al.* (1975) data.

No numerical model of the accretion flow has been constructed so far. Consequently, all the estimates above are subject to errors of a factor of 2 or so. But it has been shown that the general features of the X-ray light curve for this type of turnon transition can be understood in a consistent way within the framework of this simple model.

IV. DISCUSSION

There are three distinct theories for the origin of stellar winds (reviewed in Cassinelli, Castor, and Lamers 1978). If the gross properties of the mass-loss star (mass, luminosity, radius) vary negligibly during the transition, then neither the cool-wind model of

Castor, Abbott, and Klein (1975, hereafter CAK) nor the coronal model of Hearn (1975) predicts variation of the mass-loss rate. From the group of available theories only the imperfect flow model of Cannon and Thomas (1977) would be expected to exhibit variable flow. Unfortunately, no quantitative description of how the subatmosphere of an early-type star drives the mass loss has been given. The fact that the star is close to filling its Roche lobe (Hutchings *et al.* 1978) is probably a contributing factor to the variability.

The assumption that the mass-loss rate is prescribed by the subatmosphere, but that radiation acts to accelerate the gas to supersonic velocities, is consistent with the interpretation of the data made in this paper. The wind equation (CAK, eq. [20]) is

$$\frac{(v - c_s^2)}{v}\frac{dv}{dr} = \frac{2c_s^2}{r} - \frac{dc_s^2}{dr} - \frac{GM(1-\Gamma)}{r^2} + \frac{\Gamma GMk}{r^2} \times \left[\frac{4\pi}{\sigma_e V_{\rm th}(dM/dt)}\right]^\alpha \left(r^2 v\frac{dv}{dr}\right)^\alpha , \quad (7)$$

where c_s is the sound speed, $\Gamma = \sigma_e L/(4\pi GMc)$, $V_{\rm th}$ is the thermal velocity in the gas, and k and α are fitting parameters of an approximation for the radiation acceleration.

For the region near the star where the wind velocity is small, but supersonic, with an assumed wind temperature of less than 10^6 K, the dominant terms in the above equation (the last and next to last terms) represent a balance between the effective gravity and the radiation acceleration. The solution to this simplified equation (with the substitution of numerical values $T = 4 \times 10^4$, $k = 0.03$, and $\alpha = 0.7$, as determined by CAK) is

$$(v^2 - v_0^2)^{1/2} = 320\dot{m}_6\left(\frac{1-\Gamma}{\Gamma}\right)^{1/\alpha}\left(\frac{1}{r_{12}^0} - \frac{1}{r_{12}}\right) \text{ km s}^{-1} . \quad (8)$$

The gas enters the region of radiation acceleration at velocity V_o and radius r_{12}^0 and travels to r_{12} to obtain velocity V, where the radii are expressed in units of 10^{12} cm. This equation is analogous to equation (47) of CAK, except that the mass-loss rate here is a prescribed quantity.

Equation (8) has a number of interesting features. Using the system parameters $m = 5$, $r_{12}^0 = 1$, $r_{12} = 1.3$, and $\Gamma = 0.5$, and assuming that V_o is small yields for the X-ray high state an expected velocity of 400 km s^{-1} at the neutron star, which is in close agreement with the value deduced by Jackson and in the discussion above. If the mass-loss rate declined from a higher value, the velocity should decline as $(dM/dt + \text{constant})^{1/2}$, i.e., slightly slower than $(dM/dt)^{1/2}$. If mass conservation is required to be in the form dM/dt = constant times nvr^2, then as the mass-loss rate declines, the density should decline slightly faster than $(dM/dt)^{1/2}$.

The interpretation of the transition requires that the velocity decline more slowly than the density so that the luminosity remains approximately the same. This is possible if the initial velocity of the gas into the region of radiation acceleration is quite high, say 200–500 km s^{-1}.

V. SUMMARY

It has been argued that (1) Cen X-3 accretes matter from a supersonic stellar wind emanating from the KRZ star; (2) the turnon transitions observed by Schreier, Swartz, and Giacconi (1976) and Pounds *et al.* (1975) are both due to a declining wind density; (3) dips in the X-ray light curve can be explained by a model for supersonic accretion onto the neutron star; and (4) the changing character of the dips indicates that the radial velocity of the wind drops from about 800 km s^{-1} to 500 km s^{-1}, as the density drops from about 5×10^{11} cm^{-3} to 1×10^{11} cm^{-3}. Thus the mass-loss rate drops by a factor of about 5–10 during the transition. Since the wind from the primary is likely to be asymmetrical, the mass loss from the star as a whole may not decline by quite this much during the transition.

The variability of the mass-loss rate would seem to fit best with the ideas of Cannon and Thomas. That is, the mass-loss rate is first determined by subatmospheric processes that provide the initial acceleration for the gas; then radiation acceleration takes over to accelerate the wind to its terminal velocity.

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