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X–RAY EMISSION OF THE PULSAR–Be STAR BINARY PSR 1259–63*

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ABSTRACT

X–rays are detected from the pulsar–Be star binary PSR 1259−63 only after apastron passage. We suggest that the X–rays result from accretion on to the pulsar magnetosphere of matter captured from the Be star wind. The capture efficiency changes markedly at this phase, in line with the observations, provided that the wind is slow ($\sim$ sonic) at large distances from the Be star.

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1. INTRODUCTION

The 47.7 ms radio pulsar PSR 1259–63 discovered by Johnston et al. (1992a) is unique in having a Be star companion (Johnston et al. 1992b). The binary orbit is long (period $P_{\rm orb} = 1237$ days) and highly eccentric, and radio pulsations are observed throughout the entire orbit, except near periastron ($e = 0.87$) (Johnston et al. 1992b, 1994). These properties suggest a close relationship to the class of eccentric Be X–ray binaries such as 4U0115+63 (Cominsky et al. 1978; Rappaport et al. 1978) and A0538–66 (Skinner et al. 1982). Although the latter have much shorter orbital periods (24.3 and ~ 17 days for the two systems quoted), their periastron separations are comparable. This may imply an evolutionary connection (King 1993). Moreover, we might expect PSR 1259–63 to be a strong X–ray source near periastron passage. However, we would expect weak or undetectable X–ray emission at other orbital phases, where the neutron star is far from the Be star. The detection of X–rays by Cominsky, Roberts and Johnston (1994) near *apastron* is therefore surprising, and not easily explained by currently proposed emission mechanisms.

We study this problem further here. We suggest that the X–rays are produced by accretion of captured stellar–wind material on to the pulsar magnetosphere. The centrifugal barrier prevents this matter penetrating the light cylinder and quenching the radio pulsar. Our picture accounts self–consistently for most features of the observations, and suggests that at large distances (~ 500 stellar radii) the winds of Be stars move with rather low velocities.

2. X–RAY OBSERVATIONS

The X–ray observations of PSR 1259–63 are discussed in detail by Cominsky et al. (1994), and are summarized in Table 1. Significant X–ray emission was detected during two ROSAT PSPC pointed observations ~ 4.1 and ~ 9.6 months after apastron

Table 1: Observational Summary for PSR 1259–63[a]

Interval	Modified Julian Date	Luminosity[b] ($\times 10^{33}$ ergs s^{-1})	Days to Apastron Passage	Orbital Phase
Ginga	48505	< 0.6	-237.75	0.31
B&W	48678.68–48679.78	< 0.2	-63.5	0.45
obs1	48864.527–48869.167	3.1	124.1	0.60
obs2	49025.895–49034.539	4.2	287.45	0.73

[a] Adapted from Cominsky et al. (1994).

[b] The photon counting rates for the three ROSAT PSPC data sets were converted into luminosities in the ROSAT 0.07 to 2.4 keV band by using the fitted power law spectral parameters from the longest observation (obs2). The Ginga LAC counting rate upper limit was converted using a Crab-like spectrum, for the energy range 2 to 10 keV. All conversions assumed a distance of 1.5 kpc (Johnston et al. 1994).

passage. However, earlier observations using the Ginga LAC and the ROSAT PSPC ($\sim$ 7.9 and $\sim$ 2.1 months prior to apastron, respectively) yielded only upper limits (private communications from F. Makino and T. Aoki and from M. Bailes and N. Watson, respectively, as cited by Cominsky et al. 1994). No pulsations at the radio pulsar period were found in the detected X–rays; the upper limit on these pulsations is approximately 9% for the entire data set, or less than 0.1% of the available spin-down luminosity. The X–ray spectrum is roughly thermal, with plasma temperatures $\sim$ 1 keV in most cases, but $\sim 6 - 8$ keV for part of the second ROSAT detection. In all detections the photoelectric absorption indicated an equivalent hydrogen column density $N_H \simeq 2 - 4 \times 10^{21}$ cm^{-2}.

As discussed by Cominsky et al. (1994), none of the current models for X–ray emission (see Kochanek 1993) are easy to reconcile with these observations. The luminosity is larger by factors 15 to 700 than the coronal emission expected from the Be star corona, and the spectrum is harder than that usually observed for B and Be stars (Meurs et al. 1992). The lack of X–ray pulsations and the observed flux variations argue strongly against emission powered directly by the pulsar spin, as seen in young pulsars such as the Crab. The bow shock of the Be star wind as the neutron star moves through it might conceivably produce X–rays, but these are likely to be even weaker than the coronal emission. The energy available to be radiated by the shocked pulsar wind is, with optimistic assumptions, only barely enough to account for the observed X–rays, and it is difficult to see why it should vary with orbital phase, as observed. The visibility of any shock cone might be phase–dependent, but the fact that X–rays are first detectable almost precisely at apastron would require a rather special orientation of the binary orbit with respect to the line of sight.

Finally, the standard picture of accretion on to the neutron star of material captured from the Be star wind fails for several reasons: notably, the X–rays are not pulsed and the pulsar radio emission is not quenched. In standard accretion scenarios, the presence of radio pulsar emission should be sufficient to inhibit the plasma infall that is required to power the X–ray accretion (e.g., Stella, White, & Rosner 1986.) This mechanism should be operating in the PSR 1259–63 system, perhaps assisted by additional inhibition of plasma infall due to the propeller–like motion of the rapidly rotating magnetosphere.

3. WIND VELOCITY AND MASS CAPTURE

The above objections to accretion as the energy source for the X–rays actually only argue against accretion to *within the pulsar light cylinder*. An accretion flow halted at a larger radius would not quench the radio emission, and would probably not be strongly pulsed. In fact, as Cominsky et al. (1994) point out, the 47.7 ms spin period and magnetic field 3.3×10^{11} G inferred from the period derivative imply a centrifugal barrier to accretion down fieldlines within this radius [see Eq. (11), below]. Accordingly, we shall consider models in which accretion on to the neutron star magnetosphere powers the X–rays. We note first that all accretion–powered models place very severe restrictions on the velocity structure of the Be star wind.

The typical scale over which the neutron star can accrete matter from the Be star wind is set by the accretion radius

$$R_{\rm acc} \ = \ \frac{2GM_n}{v_{\rm rel}^2} \quad , \tag{1}$$

where M_n is the neutron star mass and

$$v_{\rm rel}^2 \ = \ (\mathbf{v}_w - \mathbf{v}_*)^2 + c_S^2 \quad . \tag{2}$$

Here $\mathbf{v}_w$ and $\mathbf{v}_*$ are the wind and neutron star velocities, and c_S the sound speed in the wind (e.g., Frank et al. 1992). If the Be star wind is emitted over solid angle Ω and carries off mass loss rate $\dot{M}_w$ we would expect the neutron star to capture roughly

$$\dot{M} \ \simeq \ \frac{\pi R_{\rm acc}^2}{\Omega r^2} \ \dot{M}_w \quad , \tag{3}$$

where r is the distance between the two stars, provided that the wind extends at least to distance $R_{\rm acc}$ from the neutron star in all directions. As Be star winds are thought to be partially confined to the equatorial plane (e.g., Waters et al. 1988), we must check that the wind's vertical extent satisfies this condition. In fact, we shall always find $R_{\rm acc}/r \lesssim 0.1$, whereas the wind's aspect ratio is probably larger than this. Thus Eq. (3) with $\Omega \sim \pi$ is reasonable in all cases.

Current models of Be winds invoke two components (e.g., Waters et al. 1988.) The high–density low–velocity equatorial component is associated with the IR emission and the X-ray emission in Be binaries, while the higher–velocity low–density wind at higher latitudes is often observed in UV resonance lines. Waters et al. have used this two-component model to explain the periastron outbursts in many X–ray Be binaries, and calculate outflowing wind velocities ranging from 150 to 600 km s^{-1}, in agreement with those derived from observations of IR excess. Further evidence that Be wind velocities are $\sim$ 100 km s^{-1} is given by the equilibrium spin-up line for most Be X–ray binaries which cannot be explained by higher velocities for the accreted material (Corbet 1984, 1986; van den Heuvel and Rapapport 1987).

The suggested wind speeds of ∼100 to 600 km s^{-1} would dominate the estimate of $v_{\rm rel}$ and $R_{\rm acc}$, as $|\mathbf{v}_*|, c_S << 100$ km s^{-1}, giving $R_{\rm acc} \sim 10^{10}$ cm. At apastron $r \sim 10^{14}$ cm, so Eq. (3) implies that the neutron star captures only a fraction $\sim 10^{-8}$ of the wind. With typical Be star mass–loss rates, $\dot{M}_w \sim 10^{-8}{\rm M}_\odot$ yr^{-1}, the neutron star would capture only $\sim 10^{10}$ g s^{-1}. The observed $L_X \sim 10^{33}$ erg s^{-1} then requires that $\sim 10^{23}$ erg should be extracted from each gram, which is 100 times the rest-mass energy. Short of invoking relativistic effects, it is clear that accretion from a wind with $|\mathbf{v}_w|$ of anything like the suggested order of $\gtrsim 100$ km s^{-1} is quite incapable of powering the observed X–rays.

We may generalize this argument: the observation that the radio pulses are not quenched sets a limit on the efficiency of energy extraction from accreting matter, and thus on $v_{\rm rel}$. Since the infalling gas must not penetrate the light cylinder, the accretion luminosity is

$$L \le \frac{GM_n\dot{M}}{R_{\rm L}} \tag{4}$$

where $R_{\rm L} = 2.5 \times 10^8$ cm is the light–cylinder radius. Using (3) for $\dot{M}$ gives

$$\frac{R_{\rm acc}}{r} \ge \left[\frac{\Omega}{\pi}\,\frac{LR_{\rm L}}{GM_n\dot{M}_w}\right]^{1/2} . \tag{5}$$

The escape velocity from the binary at radial distance r is $v_{\rm esc} = (2GM/r)^{1/2} \simeq 40$ km s^{-1} at apastron, where M is the total binary mass, since $M >> M_n$ (Be star mass $>> M_n$). Using Eq. (1), we get

$$\frac{v_{\rm rel}}{v_{\rm esc}} \le \left(\frac{M_n}{M}\right)^{1/2}\left[\frac{\pi}{\Omega}\,\frac{GM_n\dot{M}_w}{LR_{\rm L}}\right]^{1/4} . \tag{6}$$

With $M_n = 1.4{\rm M}_\odot, {\rm M} = 11{\rm M}_\odot, \Omega \sim \pi, \dot{\rm M}_{\rm w} = 10^{-8}{\rm M}_\odot$ yr$^{-1}, L = 10^{33}$ erg s^{-1} and $R_{\rm L} = 2.5 \times 10^8$ cm we find $v_{\rm rel}/v_{\rm esc} \lesssim 1.4$. Since the neutron star's orbital velocity is $v_* = [(1-e)/2]^{1/2} v_{\rm esc} \simeq 0.25 v_{\rm esc}$ near apastron in PSR 1259–63, we have

$v_{\rm rel} \simeq v_{\rm esc}$. In other words, if the X–rays from PSR 1259–63 are powered by accretion, the Be star wind must have a velocity at most of order escape, rather than the $\gtrsim 100$ km s^{-1} sometimes assumed. One possibility is that the equatorial wind is Keplerian ($v_w = 0.7 v_{\rm esc}$). A value of $v_{\rm rel}$ less than escape may well be appropriate in view of the fact that not all of the accretion luminosity has to be radiated as X–rays, so that L may be larger than the 10^{33} erg s^{-1} assumed in the estimate above.

4. MAGNETOSPHERIC ACCRETION

We have seen that a neutron star mass capture rate $\sim 10^{-10}{\rm M}_\odot$ yr^{-1} $\sim 10^{16}$ g s^{-1} in PSR 1259–63 is reasonable provided that the wind velocity is low near apastron. In this Section we construct a simple model of the X–ray emission in which this matter is accreted onto the neutron–star magnetosphere and then expelled centrifugally. The analytic estimate by King (1991; his Eq. 11) suggests that matter captured from the stellar wind has too little angular momentum to form an accretion disc about the neutron star in most Be–star binaries. Using the value of $v_*^2/v_{\rm rel}^2 \lesssim 0.25$ inferred above, the masses and binary period of PSR 1259–63 imply a circularization radius $R_{\rm circ} \lesssim 2.7 \times 10^8 \eta^2$ cm. Here $\eta < 1$ is an efficiency factor for the capture of angular momentum from the wind which is very unlikely to approach unity (compare with the analytic estimates of Davies & Pringle 1980 and numerical simulations by, for example, Blondin et al. 1990 for somewhat faster winds that yield very small efficiencies $\eta \lesssim 0.05$).

Thus $R_{\rm circ} < 2.7 \times 10^8$ cm, which is smaller than the magnetospheric radius we shall estimate below. Hence there is too little angular momentum in the wind to form a disc, and gas therefore falls radially inwards in rough spherical symmetry with the free–fall velocity

$$v_{\rm ff} \;=\; \left(\frac{2GM_n}{s}\right)^{1/2} \tag{7}$$

at distance s from the neutron star. From the continuity relation

$$\dot{M} = 4\pi s^2 v_{\rm ff} \rho \quad , \tag{8}$$

we can find the density ρ, and hence the ram pressure of the infalling gas:

$$P_{\rm ram} \; = \; \rho v_{\rm ff}^2 \; = \; \frac{\dot{M}(2GM_n)^{1/2}}{4\pi r^{5/2}}. \tag{9}$$

Equating this to the magnetic pressure

$$P_{\rm mag} \; = \; \frac{\mu^2}{8\pi r^6} \quad , \tag{10}$$

where $\mu \sim 10^{30}$ G cm^3 is the neutron star's magnetic moment, determines the magnetospheric radius as

$$R_m \; = \; 5 \times 10^8 \mu_{30}^{4/7} \dot{M}_{16}^{-2/7} M_1^{-1/7} \ {\rm cm} \quad , \tag{11}$$

where $\mu, \dot{M}$, and M_n are measured in units of 10^{30} G cm^3, 10^{16} g s^{-1}, and M$_\odot$ respectively. Assuming that the accretion flow is stopped at this radius, we find an accretion luminosity

$$L_{\rm acc} \; = \; 2.7 \times 10^{33} \mu_{30}^{-4/7} \dot{M}_{16}^{9/7} M_1^{8/7} \ {\rm erg \ s^{-1}} \quad . \tag{12}$$

The density estimate, Eq. (8), allows us to find the column density of the inflow as

$$N_H \; \propto \int_{R_m}^{\infty} \rho \, {\rm d}s \quad , \tag{13}$$

which gives

$$N_H \; = \; 2.5 \times 10^{21} \dot{M}_{16}^{8/7} \mu_{30}^{-2/7} M_1^{-3/7} \ {\rm cm^{-2}} \quad . \tag{14}$$

Finally, the maximum possible X–ray temperature is given by that of a strong shock at $s = R_m$ as

$$kT < kT_s \; = \; \frac{3}{8} \frac{GM_n \mu' m_H}{R_m} \simeq 70 \mu_{30}^{-4/7} \dot{M}_{16}^{2/7} M_1^{8/7} \ {\rm keV} \quad . \tag{15}$$

Here, $\mu' m_H$ is the mean mass per particle of the flow.

The estimates (11), (12), (14), and (15) are encouraging. The magnetospheric radius where the flow is stopped is larger than the light cylinder radius, as required for consistency, and is, of course, outside the corotation radius where centrifugal and gravity forces balance. Matter coupling to the magnetosphere at R_m is therefore expelled, presumably mainly in the pulsar's equatorial plane. The predicted luminosity (12) is of order that observed in X–rays, and the hydrogen column (14) agrees with observation also. However, the shock temperature (15) is considerably higher than the observed spectral temperature. This difference is always found in observations of quasi–radial accretion, for example in the medium X–ray components of accreting magnetic white dwarfs and neutron stars (see Chapter 6 of Frank et al. 1992, for an extensive discussion). The shock temperature is essentially that of the ions, which have most of the flow's kinetic energy before the shock, whereas the spectral temperature is that acquired by the electrons through Coulomb heating by the ions. Any process cooling the electrons faster than the shocked ions can heat them will depress their temperature below T_s; the relatively tenuous flow discussed here is likely to be strongly cooled by cyclotron emission, for example. We conclude that quasi–spherical infall on to the neutron star magnetosphere explains most of the observed X–ray properties of PSR 1259–63.

5. X–RAY VARIABILITY

The one feature of the X–ray behavior of PSR 1259–63 left to account for is the fact that X–rays are detected in only two of four observations. The defining parameter in our model is the accretion rate, and there are two different ways in which it can make the X–rays unobservable. Accretion rates $\dot{M}_{16} \lesssim 0.1$ would reduce the accretion luminosity below $\sim 10^{32}$ erg s^{-1} and make them undetectable at the distance of PSR 1259–63. Accretion rates $\dot{M} \gtrsim 10^{17}$ would raise N_H above $\sim 3 \times 10^{22}$ cm^{-2}. Given the observed spectrum of the object, the X–rays would be too heavily absorbed to be detectable by

ROSAT. The X–ray variability thus probably results from changes in $\dot{M}$. The nature of these changes depends on whether we take as significant the fact that only upper limits are found before apastron, and detections after apastron. Future observations covering apastron passage (for example, by ASCA) will ultimately decide the question by demonstrating the repeatability or spectral evolution of the phase dependence, but these will take on the order of a decade because of the long orbital period.

If we dismiss the phase dependence as coincidental, we can ascribe the X–ray variability simply to changes in the Be star wind (for example, either an increase or a decrease in $\dot{M}_w$). However if the link with orbital phase is systematic, the variation must be caused by the motion of the neutron star through the stellar wind. The velocity components in a Kepler ellipse of semimajor axis a are

$$v_{*,r} \;=\; v_{\rm K}\frac{1+e\cos\theta}{(1-e^2)^{1/2}} \quad , \tag{16}$$

and

$$v_{*,\theta} \;=\; v_{\rm K}\frac{e\sin\theta}{(1-e^2)^{1/2}} \quad , \tag{17}$$

where $v_{\rm K} = (GM/a)^{1/2}$. For PSR 1259–63, we have $M \simeq 11{\rm M}_\odot$, a $\simeq 7.5\times 10^{13}$ cm and $e = 0.87$, so that

$$v_{*,r} \;=\; 78\sin\theta \ {\rm km\ s}^{-1} \quad , \tag{18}$$

and

$$v_{*,\theta} \;=\; 90(1+0.87\cos\theta) \ {\rm km\ s}^{-1} \quad . \tag{19}$$

Now from Eq. (3) and the relation

$$r = \frac{a(1-e^2)^{1/2}}{1+e\cos\theta} \quad , \tag{20}$$

we find

$$\dot{M} \propto \frac{(1+0.87\cos\theta)^2}{\{[v_{w,\theta}-90(1+0.87\cos\theta)]^2+[v_{w,r}-78\sin\theta]^2+c_S^2\}^2} \quad . \tag{21}$$

With suitable choices of $v_{w,r}, v_{w,\theta}$ and c_S the denominator of Eq. (21) can be made mainly sensitive to the term involving $v_{w,r}$ at apastron ($\theta = \pi$). The sign change of $v_{*,r}$

reduces the mass capture rate on to the neutron star quite markedly as the star passes apastron: if the $v_{w,\theta}$ and c_S terms are negligible we have $\dot{M} \sim (v_{w,r} - 78 \sin\theta)^{-4}$, which varies rapidly near $\theta = \pi$ if $v_{w,r}$ is comparable with $v_{*,r}$ there. Physically, this effect arises because before apastron the neutron star moves nearly radially outwards and is almost stationary with respect to a sufficiently slow outflowing wind, whereas after apastron the relative velocity of wind and star increases because the star reverses its radial motion. The c_S term always damps this effect, but $v_{w,\theta}$ may amplify or damp the change of $\dot{M}$ depending on its size. Figures 1 and 2 plot the predicted ratio of $N_H \propto \dot{M}^{8/7}$ in the Bailes and Watson pre-apastron observation to that of the post-apastron detection 'obs1' as a function of $v_{w,r}$ for various $v_{w,\theta}$, with $c_S = 0$ in Fig. 1 and $c_S = 10$ km s^{-1} in Fig. 2. The sound speed $c_S = 12T_4^{1/2}$ km s^{-1}, where T_4 is the wind temperature in units of 10^4 K. As the surface temperature of the B2e star SS 2883 (Johnston et al. 1994) is about 2×10^4 K, we would not expect c_S to exceed ~ 16 km s^{-1} in any case.

Clearly, to get any significant effect we require a fairly cool wind (temperature $\lesssim 5000$ K) which is slow ($v_{w,r} \sim v_{w,\theta} \sim 10 - 15$ km s^{-1}). Formally, it is not possible to get the required change of N_H between Observations 2 and 3 with a wind velocity corresponding to unbound material (this requires $(v_{w,r}^2 + v_{w,\theta}^2)^{1/2} \gtrsim 45$ km s^{-1}). However, given the crudeness of the estimate (3) of the capture rate, this discrepancy is probably not significant. Indeed, we have seen that the wind is not very supersonic, whereas a hypersonic wind is assumed in the reasoning leading to (3). We conclude that it may be possible to explain a systematic X–ray turn–on at apastron in terms of accretion on to the magnetosphere from a near–sonic wind at this orbital phase.

6. DISCUSSION.

We have shown that the X–ray emission from PSR 1259–63 may be reasonably explained by a model in which stellar wind material is captured, and falls quasi–spherically on to the neutron star magnetosphere. If the appearance of the X–rays at apastron is a systematic effect, this may also be understandable if the wind is almost sonic there.

The main requirement of our model is that the equatorial wind of the Be star must be very slow; i.e., at most comparable with the escape speed. This is smaller than normally found in models of Be star winds (Waters et al. 1988). However, the neutron star in PSR 1259–63 is sampling much more remote parts of these winds than normally considered (distances ~ 500 stellar radii). There is some observational evidence that the velocities of Be star winds may indeed be lower than assumed in conventional models. Although Be stars have long been known (e.g., Slettebak 1979) to exhibit large $v \sin i$ values, indicating rotation rates near breakup, observations of radial outflow velocity using UV line data have only been done for a few stars—and there is considerable disagreement as to the interpretation of these data. High-speed wind components are indicated by resonance lines of N V and Si IV, whereas low-speed wind components are indicated by studies of Fe III shell lines (Snow, Peters, & Mathieu 1979). The fact that both types of lines are found in spectra from a single star has been used as an argument for a spherically symmetric wind distribution (Doazan, Stalio, & Thomas 1982.) In contrast, high-resolution studies of UV shell lines in rapidly rotating Be stars by Oegerle and Polidan (1984) have led to the picture of a low-velocity outflowing region of the wind, which must occur in a flattened disk-like structure. Furthermore, these authors find that the velocities, relative to the star, of these lines are consistent with zero, and in no case are in excess of 40 km s^{-1}. Just as the discovery of the Be star X–ray binaries has provided additional support for the current picture of a dense, slow-moving equatorial outflow in Be stars (e.g., Waters et al. 1988), the discovery of X–rays from PSR 1259–63 may be giving clues to the wind velocity structure at large distances.

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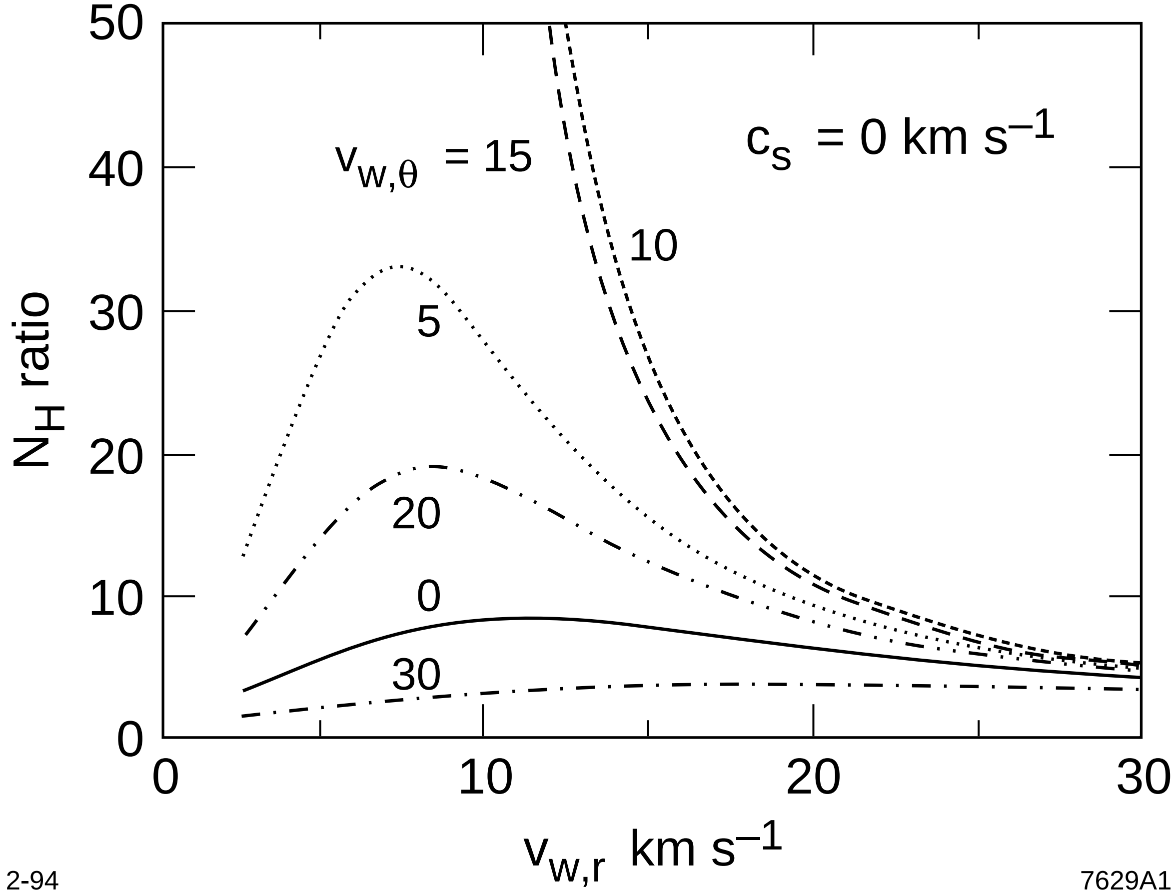

Figure 1. The ratio of the hydrogen column density, N_H for the pre-apastron Bailes and Watson (B&W) observation to the post-apastron detection "obs1" (Cominsky et al. 1994). Six models are shown with different values of the azimuthal stellar wind velocity component, $v_{w,\theta}$ as a function of $v_{w,r}$. In all models, the value of the sound speed in the wind, c_S, is assumed to be zero. An N_H ratio $\gtrsim 10$ can account for the difference in flux between these two observations.

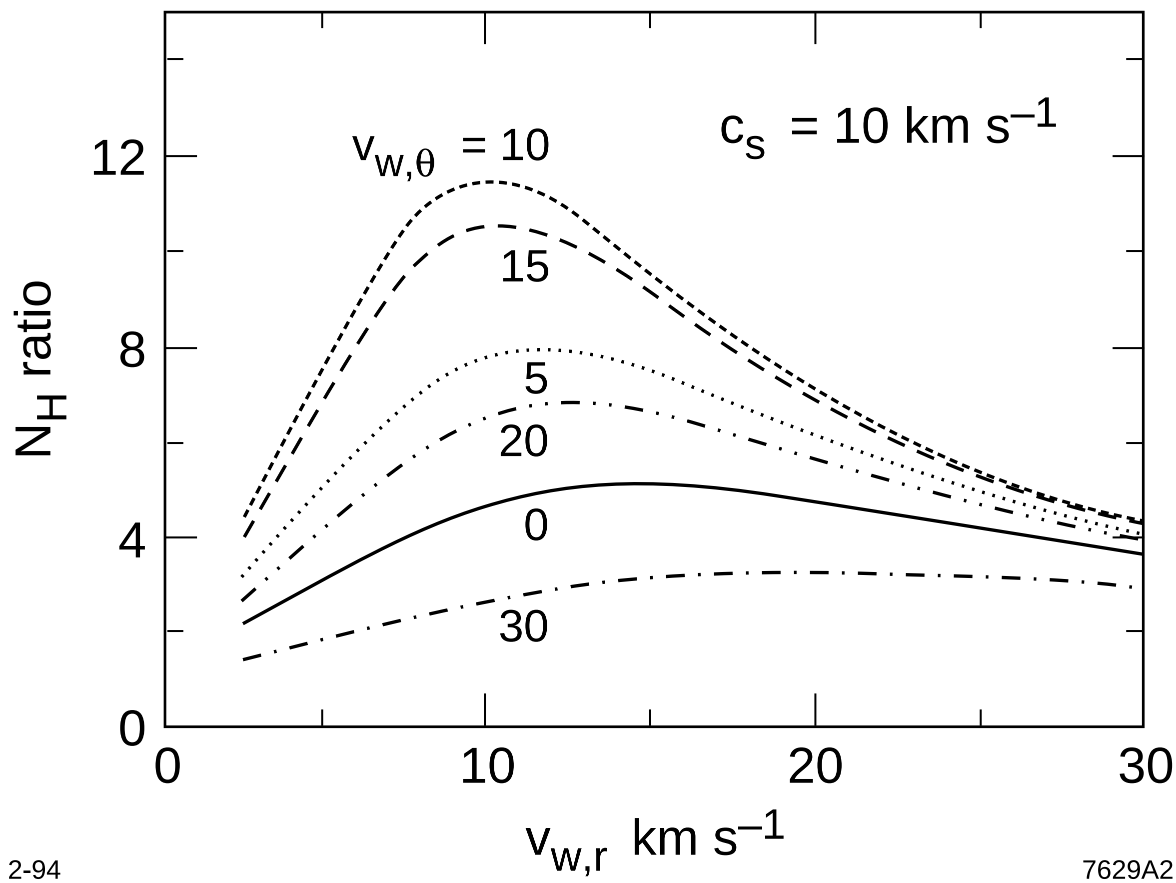

Figure 2. The same models as in Figure 1, but in this case, the sound speed in the wind, c_S, is assumed to be 10 km s^{-1}.