

PROPERTIES OF THE MASSIVE X-RAY BINARY 4U 1700–37 = HD 153919

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ABSTRACT

We re-examine the system parameters for the massive X-ray binary (MXRB) 4U 1700–37 in the light of modern spectroscopic theory and new ultraviolet and X-ray data. This system is composed of HD 153919, an O6f star having a stronger wind, and an accreting neutron star. In interpreting X-ray light curves for this system obtained from various X-ray experiments operating at different energies, we take into account the opacity of the wind to low-energy X-rays. Upon adopting the X-ray light curve from a high-energy experiment, *OSO 8*, we derive the following properties for the Of star: $M_{\text{O}} = 52 \pm 2 M_{\odot}$, $T_{\text{eff}} = 42,000 \text{ K}$, $\log g = 3.6$; a binary separation, $a = 2.0 R_{\odot}$; and a neutron-star mass, $M_{\text{x}} = 1.8 \pm 0.4 M_{\odot}$. These revised parameters for the Of component are in accord with the parameters of single Of stars, and hence, the problem that “the O star is undermassive by a factor of 2” (Conti 1978) is resolved.

The revised value for the binary separation, a , results in improved parameters for the wind from the Of star: (1) the ratio of terminal velocity of the wind to photospheric escape velocity agrees with those of single O stars; (2) the discrepancy between the values of the wind acceleration parameter, β , derived from X-ray and UV data is resolved; and (3) the acceleration of the wind is similar to that of single OB star winds.

Finally, the revised system parameters aid in our understanding of the evolutionary history of the binary. We suggest that the supernova explosion producing the neutron star in 4U 1700–37 occurred over a million years ago when HD 153919 was still on the main sequence. The explosion nearly disrupted the system, leaving the stellar components in highly eccentric orbits. Since then, HD 153919 has evolved off the zero-age main sequence to become an O supergiant with an intense wind, which serves to power the X-ray emission.

Subject headings: binaries: eclipsing — stars: emission-line, Be — stars: individual (HD 153919) — stars: neutron — ultraviolet: stars — X-rays: stars

1. INTRODUCTION

Massive X-ray binaries (MXRBs) are X-ray sources consisting of a collapsed stellar remnant (usually a neutron star, sometimes a black hole) orbiting an O- or B-type companion. X-radiation is produced by the accretion of material from the OB star by the collapsed component. In the case of the MXRB, 4U 1700–37, the collapsar is a neutron star (although not a pulsar) and the accreted material comes from the wind of the optical counterpart, HD 153919, an O6f star.

Despite the fact the 4U 1700–37 is probably one of the most intensively observed MXRBs, there are still many contradictions and discrepancies that cloud our understanding of this system. First and foremost is the problem of the mass of the optical primary (Conti 1978). The mass of HD 153919 derived from orbital analysis ($27 M_{\odot}$, Hutchings 1976) is a factor of 2 lower than the mass inferred from its spectral type or position on an H-R diagram. If HD 153919 is truly undermassive by a factor of 2, it has serious implications for our understanding of O-type spectra, the evolution of early-type close binaries, and the relation between the properties of a high-velocity wind and its underlying star. For example, the observed terminal velocity of the wind, $V_{\infty} = 2100 \text{ km s}^{-1}$, is over 10 times larger than the photospheric escape velocity. Theory (Abbott 1982) and observation (Howarth & Prinja 1989) indicate that $V_{\infty}/V_{\text{esc}}$ is usually ~ 3 and never above 4 for single O stars. In addition, the velocity law for the wind derived from X-ray data (Haberl, White, & Kallman 1989) rises much more steeply than is

known to be the case for single O stars. Either the winds from O stars in MXRBs are very different from winds in single O stars, or the stellar and system parameters for 4U 1700–37 are in error.

Since the 1970s when the basic parameters of 4U 1700–37 were derived, there have been enormous advances in the theory of radiatively driven winds and in non-LTE theory of stellar atmospheres (Kudritzki & Hummer 1990). Also since 1978, the *IUE* satellite has provided phase-resolved, high-resolution spectra of HD 153919, allowing a detailed monitor of the wind. In this paper, we take advantage of these theoretical and observational advances and apply them to the case of 4U 1700–37. In § 2, we describe the UV spectral characteristics of HD 153919 as derived from *IUE* observations and show that they are similar to those of single stars of the same spectral type. In § 3, we re-examine the orbital solution for 4U 1700–37 in the light of modern wind theory. In particular, we take into account the fact that a dense wind such as that from HD 153919 is optically thick to low-energy X-rays (van Paradijs et al. 1978; Dolan et al. 1980). We show how the optical thickness of the wind to low-energy X-rays can cause an overestimate of the duration of X-ray eclipse and hence, an underestimate of the mass of HD 153919. Using reasonable values of the orbital inclination and duration of X-ray eclipse, we then derive a mass of HD 153919 which is nearly double the value derived by Hutchings (1975) and in fair agreement with the mass of the star as deduced from its spectroscopic properties as well as its location on the H-R diagram. In § 4, we show that the revised parameters result in a velocity law and terminal velocity of the wind that are consistent with observation and in agreement with the winds of single O stars. Finally, in § 5, we use the

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revised stellar parameters to infer the evolutionary history of the system.

2. ANALYSIS OF *IUE* SPECTROGRAMS

The *IUE* archives presently contain 61 high-dispersion, short-wavelength (1150–1950 Å) spectrograms of 4U 1700–37. All are relatively short exposures (30 minutes) compared to the orbital period (3.41 days) and, hence, have excellent phase resolution. We obtained all 61 of these spectrograms from the archives and reduced them to form single vectors of wavelength and flux. For those spectrograms obtained early on in the lifetime of *IUE* (SWP 19000 and earlier), we reprocessed the original echellograms using current software (Feggans et al. 1988), so as to have a homogeneous data set. Below, we describe the spectral properties of HD 153919 as deduced from *IUE* spectrograms: its UV spectral classification, photospheric radial velocity curves, and the terminal velocity of the wind.

2.1. UV Spectral Characteristics of HD 153919

Figure 1 shows a typical high-dispersion spectrum of 4U 1700–37. This observation was obtained near the midpoint of X-ray eclipse ($\phi = 0.02$). In the ultraviolet, only the optical primary, HD 153919, is visible. The dominant features are emission and P Cygni lines formed in the wind from HD 153919. While the N v $\lambda\lambda 1238, 1242$ doublet is poorly defined because of blending with interstellar Ly α , the Si iv $\lambda\lambda 1393, 1403$ and C iv $\lambda\lambda 1548, 1550$ doublets show well-defined but saturated P Cygni profiles. In addition, both He ii $\lambda 1640$ and N iv $\lambda 1718$ show P Cygni profiles. The photospheric absorption spectrum is rich, with the most prominent photospheric

features being O iv $\lambda\lambda 1338, 1342$, N iii $\lambda\lambda 1747, 1752$, and numerous blends of Fe and Ni lines.

We compared this spectrum to those of single O stars displayed in the *IUE* Spectroscopic Atlas of O Stars (Walborn, Nichols-Bohlin, & Panek 1985). C iv $\lambda\lambda 1548, 1550$ is not quite as strong as Si iv $\lambda\lambda 1393, 1403$, suggesting a type of O6.5 or later. On the other hand, He ii $\lambda 1640$ appears in emission, indicative of a spectral type somewhat earlier than O6 (Walborn & Nichols-Bohlin 1987). At spectral type O6, Si iv $\lambda\lambda 1393, 1403$ is a discriminant of luminosity class, appearing as a strong P Cygni feature only for class Ia. We conclude that HD 153919 has the UV spectral characteristics of an O6.5Iaf star, in agreement with visual estimates (O6.5f; Wolff & Morrison 1974; O6f, Conti & Cowley 1975).

One of the spectra in the *IUE* Atlas is the spectrum of λ Cephei, a single star having the same spectral type (O6 Iaf) and edge velocity of the wind (2500 km s^{-1}) as HD 153919. Pauldrach, Puls, & Kudritzki (1986) derived the following parameters for this star: $T_{\text{eff}} = 42,000 \text{ K}$, $\log g = 3.7$, and $R = 17 R_{\odot}$, and hence, $M = 52.6 M_{\odot}$, and $L = 8 \times 10^5 L_{\odot}$. Since HD 153919 and λ Cep are nearly identical spectroscopically, we tentatively adopt these parameters for HD 153919, but with two provisos pointed out by Kudritzki & Hummer (1985). First, the derived effective temperature may be overestimated by 10%, since the photospheric model of Pauldrach et al. did not include the effects of wind-blanketing. Second, the gravity may be underestimated by 0.15 dex, because their model took into account radiation pressure in the continuum but not in the lines. We will show in § 3 that these spectroscopic parameters are consistent with those derived from an orbital solution.

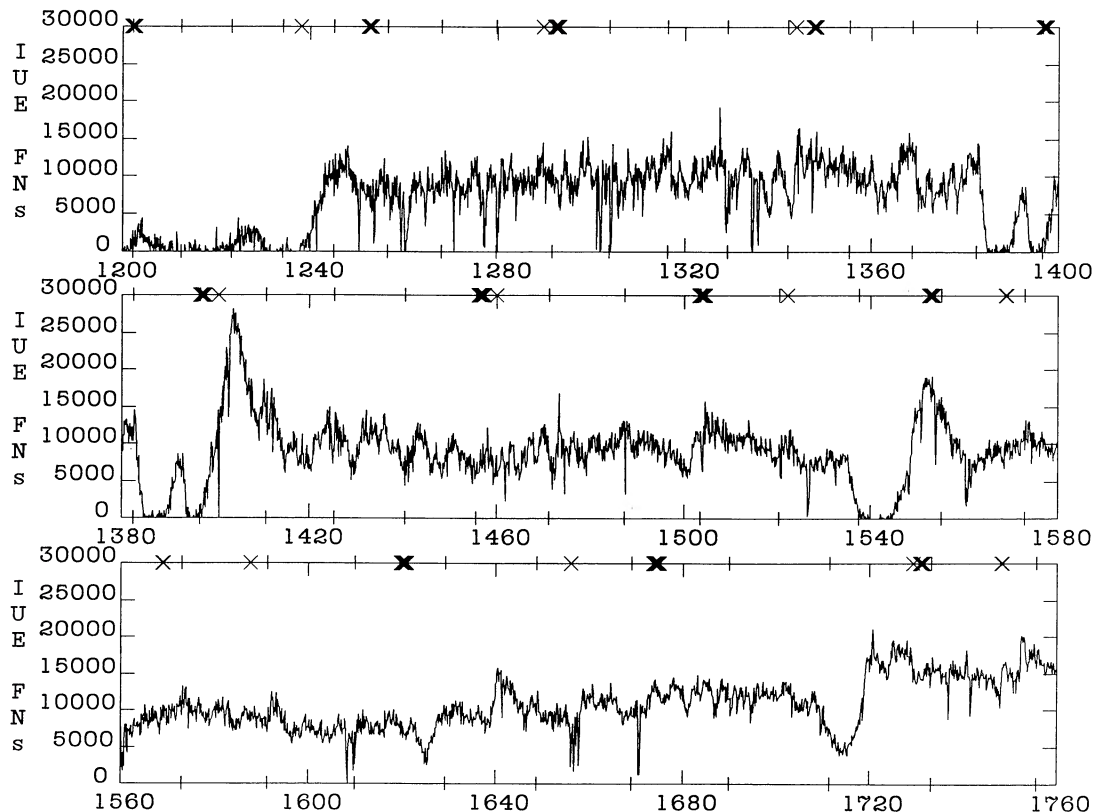


FIG. 1.—*IUE* spectrum (image SWP 1714, $\phi = 0.02$) of HD 153919 from $\lambda\lambda 1200$ –1760 Å. Bad data points are marked by a cross (x); interorder splice points are marked by full ticks on the abscissae.

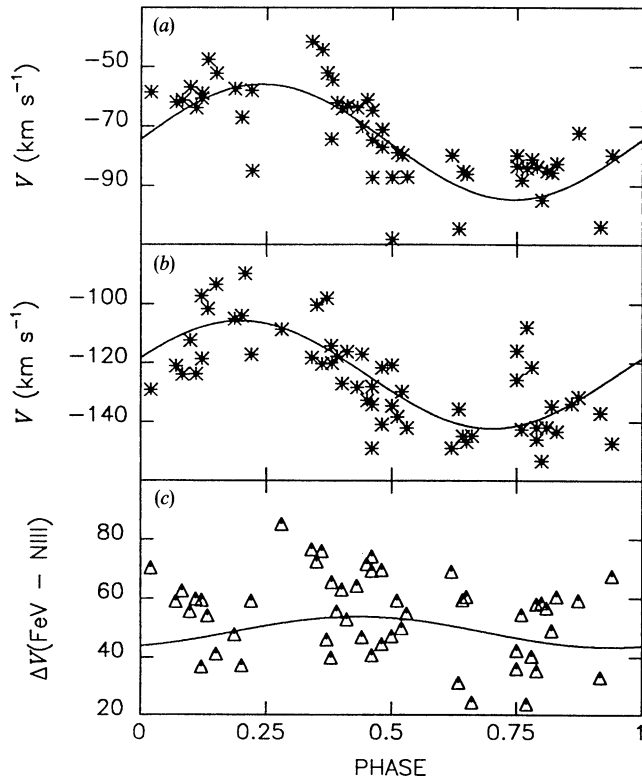


FIG. 2.—(a) Radial velocity curve for Fe v (1307–1320 Å) and solution. (b) Radial velocity curve for N III (1740–1765 Å) and solution. (c) Radial velocity gradient within the O-star atmosphere derived from measures of Fe v and N III lines.

2.2. UV Radial Velocity Curves

Because the UV spectrum of HD 153919 has such a rich photospheric spectrum, it is ideal for tracking phase changes in radial velocity due to the motion of the Of star around the center of mass of the system. We constructed radial-velocity curves in order to derive an improved value of the semi-amplitude, K_0 . In addition to the 40 spectra used by Hammerschlag-Hensberge, Howarth, & Kallman (1990, hereafter HHK) (listed in their Table 1), we also measured an additional 21 high-dispersion spectra from the *IUE* archives for added phase coverage.

We first measured changes in radial velocity by cross-correlating selected regions of a spectrum containing strong photospheric features with the same regions in a fiducial spectrum, chosen to be SWP 25596. We then added in the heliocentric correction as determined by direct measurement of SWP 25596. Table 1 lists the wavelength region analyzed, the dominant spectral feature in the region, and formal (least-

squares) solution and associated uncertainty. Figure 2 shows velocity curves for Fe v and N III along with the formal solutions. Some of the scatter is undoubtedly real and due to profile variations that are not necessarily phase locked. Such variability is also evident in visible-band data. Conti & Cowley (1975) found that the radial velocity of a given line may vary on time scales much longer than the orbital period. Since the *IUE* data span almost 10 yr, such temporal variability is bound to introduce scatter. However, restricting the UV data to a subset which spans a smaller time interval also restricts the phase coverage and does not result in substantially better velocity curves.

Our estimate of $K_0 = 18 \text{ km s}^{-1}$ is slightly lower than $K_0 = 20 \text{ km s}^{-1}$ derived by Hutchings (1975) and adopted by Conti (1978). Nevertheless, if we omit the velocities of lines that Hutchings judged uncertain, we obtain $K_0 = 16 \text{ km s}^{-1}$ from his data. Considering our results also with those of Hammerschlag-Hensberge (1988), Wolff & Morrison (1974), we adopt $K_0 = 18 \pm 2 \text{ km s}^{-1}$.

2.3. Terminal Velocity of the Wind

The velocity law for a radiatively driven wind is usually specified as

$$V(r) = V_\infty(1 - R_0/r)^\beta, \quad (1)$$

where V_∞ is terminal velocity of the wind and β is an acceleration parameter. Because of ‘turbulence’ in the wind, the terminal velocity of the wind can be significantly lower than the edge velocity of the absorption component of a P Cygni line profile. We therefore determined the terminal velocity of the wind from HD 153919 by fitting theoretical profiles generated by the SEI method (Lamers, Cerutti-Sola, & Perinotto 1987) to the Si IV and C IV P Cygni profiles in a spectrogram (SWP 1714) obtained near midpoint of X-ray eclipse. The terminal velocity so determined is $V_\infty = 2100 \text{ km s}^{-1}$, with a turbulent velocity $V_{\text{turb}} = 200 \text{ km s}^{-1}$ and $\beta \sim 1.0$, in agreement with the measurements of Howarth & Prinja (1989) for this star.

3. SYSTEM PARAMETERS

Mass ratios for X-ray binary systems may be obtained directly if the collapsed component is an X-ray pulsar, since the periodic Doppler shift of the X-ray pulsation period can be used to determine the X-ray mass function. Unfortunately, no stable X-ray pulsations have ever been recognized from 4U 1700–37, although X-ray periods ranging from 67 s to 97 minutes have been suggested (Murakami et al. 1984; Matilsky, La Sala, & Jessen 1978). We checked four archival *Einstein* Monitor Proportional Counter observations of 4U 1700–37 (MPC 1528, 3751, 6622, and 7398) for evidence of any modulation of the X-ray flux on time scales of minutes. While vari-

TABLE 1
ORBITAL ELEMENTS

Region (Å)	Dominant Ion	γ^a (km s ⁻¹)	K (km s ⁻¹)	ω	e	χ^b (eV)
1307–1330.....	Fe v	–75 (8)	19 (5)	346° (15)	0.003 (0.004)	57
1336–1350.....	O IV	–17 (11)	18 (3)	359 (10)	0.006 (0.003)	55
1415–1450.....	Fe v	–72 (12)	23 (6)	359 (9)	0.001 (0.003)	57
1740–1765.....	N III	–125 (7)	18 (3)	359 (9)	0.003 (0.002)	30

^a Numbers in parentheses are estimates of 1σ errors.

^b χ = IP of next lowest ionization stage, or EP of lower level, whichever is higher.

ations on a time scale of tens of minutes could be seen in this data set, time-series analysis did not reveal any stable, periodic variations.

Because no stable X-ray pulsations have been observed from this system, the X-ray mass function cannot be determined, and thus, the physical parameters of the binary (M_O , M_X , R_O , a) cannot be derived directly. Nevertheless, the radial velocity curve of the O star, together with the duration of the X-ray eclipse can be made to yield these parameters if the radius of the O star and the orbital inclination can be estimated. In fact, previous determinations of the system parameters (Hutchings 1974, 1975; Wolff & Morrison 1974) proceeded along these lines. Because these analyses resulted in too low a mass for the O star, we re-examine the determination of the system parameters based on current observational evidence and modern spectroscopic theory.

The method used is straightforward (e.g., Aitken 1964) and can be summarized as follows. The mass of the secondary is related to the O-star mass function, $f(M_O)$, and the total system mass:

$$M_X^3 \sin^3 i = f(M_O)(M_O + M_X)^2. \quad (2)$$

Here M_O and M_X are the masses of the O star and the neutron-star companion, respectively, and i the orbital inclination. The O-star mass function (in solar masses) is given by

$$f(M_O) = 1.038 \times 10^{-7} K_O^3 P(1 - e^2)^{3/2}, \quad (3)$$

where K_O is the projected velocity semi-amplitude of the O star (in km s^{-1}), e the orbital eccentricity, and P the orbital period (in days). Furthermore, the total mass of the system is related to the separation of the binary components, a , via Kepler's third law:

$$M_O + M_X = 0.0133 \frac{a^3}{P^2} \quad (4)$$

if the masses are in solar masses, the separation a in solar radii, and the period in days. Since the neutron-star companion is a point mass, the duration of X-ray eclipse provides a relation between a and the radius of the O star, R_O :

$$a = \frac{R_O}{\sqrt{\cos^2 i + \sin^2 i \sin^2 \theta_E}}, \quad (5)$$

where θ_E is one-half the duration of the X-ray eclipse, expressed as an angle. Thus, determination of θ_E (and reasonable estimates for R_O and i) allows the determination of a by equation (5), which in turn gives the total system mass by equation (4). The mass function of the O star (eq. [3]) and the total system mass then yield the mass of the secondary by equation (2). The mass of the O star is determined by subtracting M_X from the total system mass. Thus, knowledge of the orbital parameters, K_O , θ_E , P , and i , along with the stellar radius, R_O , allow a determination of the basic system parameters, M_O , M_X , and a .

For our purposes, the orbital period, inclination ($i > 80^\circ$), and velocity semi-amplitude ($K_O = 18 \pm 2 \text{ km s}^{-1}$) are well known. The radius of the O star is less well known. Conti (1978) gives the radius of HD 153919 as $21.9 R_\odot$, while Howarth & Prinja (1989) suggest $R_O = 24 R_\odot$, and Pauldrach et al. (1986) derive $17 R_\odot$ for O6f-type stars like HD 153919. We allow R_O to lie in the range, $17\text{--}20 R_\odot$. The half-angle of eclipse, θ_E , has considerable uncertainty. Published values of θ_E fall over a wide range, $30^\circ \leq \theta_E \leq 58^\circ$ (Jones et al. 1973;

Branduardi, Mason, & Sanford 1978; Haberl et al. 1989). Two factors contribute to the large uncertainty. First, the X-ray flux is subject to flaring, so that ingress and egress are not smooth curves; and in between flares, the X-ray flux can drop down to eclipse levels (Haberl et al. 1989). Worse, the wind from the O star can severely attenuate the X-ray emission from the neutron star, simulating eclipse and causing an overestimate of θ_E (Dolan et al. 1980). Since the opacity of the wind to X-rays decreases toward higher energies, the duration of X-eclipse is best estimated by high-energy detectors. Dolan et al. monitored the high-energy X-ray flux (20–150 keV) from 4U 1700–37 with *OSO 8* and found a substantially shorter eclipse ($\theta_E \sim 25^\circ$), although their phase resolution was poor due to the long integration time required. Van Paradijs et al. (1978) derived a similar value ($\theta_E = 25^\circ \pm 6^\circ$) from comparing the midpoint of X-ray eclipse derived from optical photometry and spectroscopy and the observed exit from X-ray eclipse. For our analysis, we adopt $\theta_E = 30^\circ \pm 5^\circ$.

As shown in Table 2, a value of $\theta_E \sim 40^\circ\text{--}50^\circ$, as suggested by most low-energy X-ray light curves and as adopted by Conti (1978), leads to an O-star mass, $M_O = 27 M_\odot$, which is nearly a factor of 2 lower than the masses of single O6f stars. In addition, the surface gravity of HD 153919 is unreasonably low, and the ratio of escape velocity to terminal velocity of the wind is unreasonably high. For the same stellar radius as above, a lower value of $\theta_E \sim 30^\circ$ yields higher component masses: $52 \pm 2 M_\odot$ for the O star and $1.8 \pm 0.4 M_\odot$ for the neutron star. Figure 3 illustrates this point graphically by showing a contour plot of O-star and neutron-star masses for a range of θ_E and R_O . As shown in Table 2, the O-star mass, surface gravity and V_∞ - V_{esc} relation are now compatible with those of single Of stars.

We have examined the latter point in some detail by making use of the analytic 'recipe' of Kudritzki et al. (1989) for determining the terminal velocity of the wind for a given escape velocity. The calculated terminal velocity depends strongly on the value of α , which specifies the dependence of the line force multiplier on the optical depth in the wind, and to a lesser extent on δ , which describes the ionization structure of the wind. For this study, we chose the wind parameters of Kudritzki, Pauldrach, & Puls (1987) for stars of normal metallicity:

TABLE 2
REVISED SYSTEM PARAMETERS

Parameter	Conti	This Paper
$\Theta_E (^\circ)$	44	30 ± 5
$K (\text{km s}^{-1})$	20	18 ± 3
$M_O (M_\odot)$	27	52 ± 2
$M_X (M_\odot)$	1.3	1.8 ± 0.4
$R_O (R_\odot)$	20	18 ± 3
$a \sin i (R_\odot)$	1.35	2.0 ± 0.4
$T (\text{K})$	40000	42000 ± 2000
$\log g_O$	3.27	3.65 ± 0.15
$\log L_{\text{bol}}/L_\odot$	5.97	5.95 ± 0.12
Γ^a	0.92	0.47 ± 0.13
$V_{\text{esc}} (\text{km s}^{-1})^b$	203	766 ± 162
V_∞/V_{esc}	10.3	2.7

^a Ratio of stellar to electron-scattering (Eddington) luminosity: $\Gamma \approx 2.7 \times 10^{-5} L/M$, with L and M in solar units.

$$^b V_{\text{esc}} = 619 \sqrt{\frac{M_O}{R_O} (1 - \Gamma)} \text{ km s}^{-1}.$$

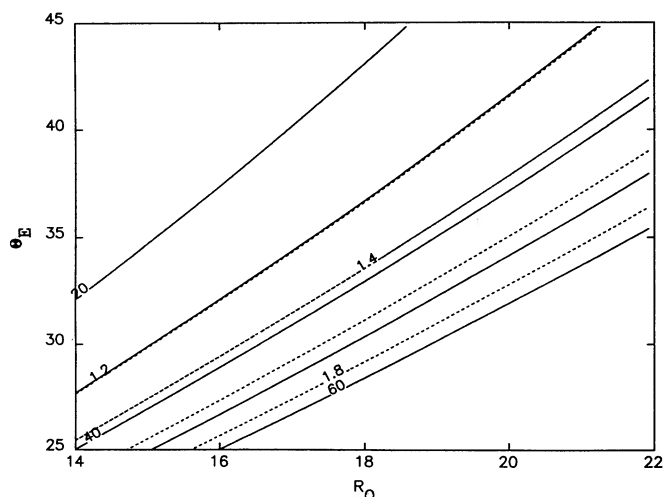


FIG. 3.—Dependence of stellar masses on eclipse duration and O-star radius. Solid lines give the O-star mass as annotated, while dashed lines give the mass of the neutron star. The calculations assumed $K_O = 18 \text{ km s}^{-1}$, $i = 90^\circ$, $P = 3.4117 \text{ days}$.

$\alpha = 0.59$ and $\delta = 0.09$ for $T_{\text{eff}} = 38,000 \text{ K}$, or $\alpha = 0.64$ and $\delta = 0.07$ for $T_{\text{eff}} = 42,000 \text{ K}$. We obtain $V_\infty = 1690$ and 2370 km s^{-1} for the two effective temperatures, which nicely bracket the observed $V_\infty = 2100 \text{ km s}^{-1}$.

We conclude that our solution yields stellar parameters for HD 153919 that are compatible with those of single stars of the same spectral type and a mass for the neutron star that is compatible with the canonical value ($M_x = 1.4 M_\odot$). In the next section, we show that our solution also yields parameters for the wind that are both internally consistent and compatible with those of single stars of the same spectral type.

4. PROPERTIES OF THE WIND

The wind acceleration parameter, β , in equation 1 is an important parameter, since it relates the outflow velocity to the distance from the star, and it defines the density structure of the wind through the conservation of mass equation. The value of β can be derived from the profiles of UV wind lines or from X-ray light curves. Physical consistency requires that the UV and X-ray estimates be the same. However, if Conti's component separation, $a = 1.45R_O$ is assumed, the X-ray data yield a $\beta \approx 0.4$ (Haberl et al. 1989), while the UV wind lines indicate $\beta \approx 1.0$ (HHK). Below, we show that this apparent discrepancy is due entirely to the choice of eclipse duration, θ_E , and that both the UV and X-ray data are consistent with a $\beta \sim 1.0$.

Phase changes in the wind lines.—X-ray radiation near the neutron star will alter the ionization state of the wind near the X-ray source, creating a roughly spherical 'Strömgren sphere' or 'ionization cavity' around the neutron star (Hatchett & McCray 1977). The presence of such a region in the wind is revealed by a decrease in the absorption component of a P Cygni feature when the cavity is in front of the O star ($\phi = 0.5$). For the case of 4U 1700–37, the presence of an ionization cavity is most evident in phase changes in *unsaturated* wind lines, such as N IV $\lambda 1718$. Howarth et al. (1986) showed that at X-ray eclipse ($\phi = 0.5$) the absorption in this wind line is diminished in the velocity range, -1400 to -780 km s^{-1} . Figure 4, which plots the strength of N IV 1718 as a function of phase, indicates that the absorption is diminished over the phase range, $\phi = 0.35$ – 0.65 . We now use these velocity and

phase constraints to infer the physical location and size of the ionization cavity.

Surfaces of constant ionization within the cavity, denoted by q_x , are specified by (Hatchett & McCray 1977):

$$q_x = \left(\frac{r}{d_x} \right)^2 \left[\frac{V(r)}{V(a)} \right], \quad (6)$$

where r and d_x are the distances to a point on the q_x surface from the center of the O star and from the collapsed companion, respectively, and the ratio, $V(r)/V(a)$ is calculated via equation (1). As discussed above, phase changes in the N IV $\lambda 1718$ line profile requires that the cavity remove N^{+3} absorbers in the phase range, 0.35 – 0.65 , and within the velocity range, -1400 to -780 km s^{-1} , when viewed at $\phi = 0.5$. As shown in Figure 5, these two constraints cannot be satisfied simultaneously for any value of q_x if β is as small as 0.5 . However, a $q_x = 8.0$ surface fits nicely within the velocity space constraints at $\phi = 0.5$ if $\beta = 1.0$.

X-ray light curves.—Figure 6 shows the observed phase variation of the wind column density to the neutron star as reconstructed from the X-ray data of Haberl et al. (1978, their Fig. 8). Superposed on this plot are calculated curves for different assumed wind parameters, β and V_∞ . We calculated the column density of the wind along the line of sight, z , to the neutron star as

$$N_H = \int_0^\infty n(r_z) dz, \quad (7)$$

where $n(r)$ is the density of the wind at a distance, r , from the O star:

$$n(r) = \frac{\dot{M}}{4\pi V_\infty \mu m_H r^2 (1 - R_O/r)^\beta} \quad (8)$$

and $r_z^2 = z^2 + a^2 - 2az \cos \phi$, and $\mu = 1.3$ is the mean atomic weight of the wind. The solid line shows the dependence of N_H on ϕ for our system and wind parameters ($R_O = 18R_\odot$, $a = 2R_O$, $\dot{M} = 6 \times 10^{-6} M_\odot \text{ yr}^{-1}$, $V_\infty = 2100 \text{ km s}^{-1}$, and $\beta = 1$). These parameters produce a good match to the observations. For comparison, the dashed line shows the variation of N_H with ϕ for our system and wind parameters except that $V_\infty = 2600 \text{ km s}^{-1}$, which is the terminal velocity assumed by Haberl

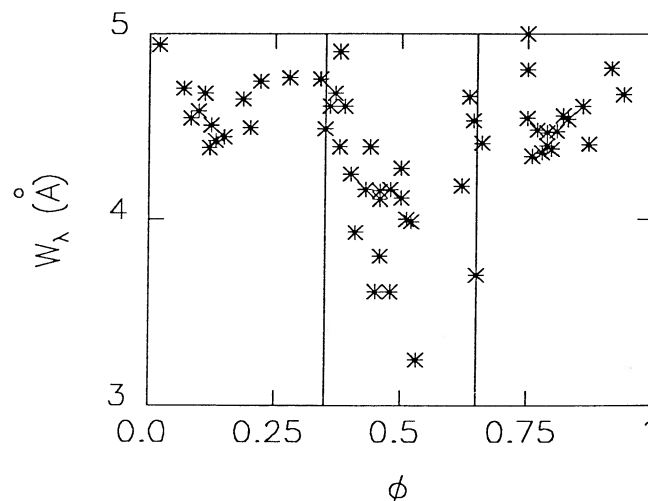


FIG. 4.—Equivalent widths of the N IV $\lambda 1718$ absorption feature vs. phase.

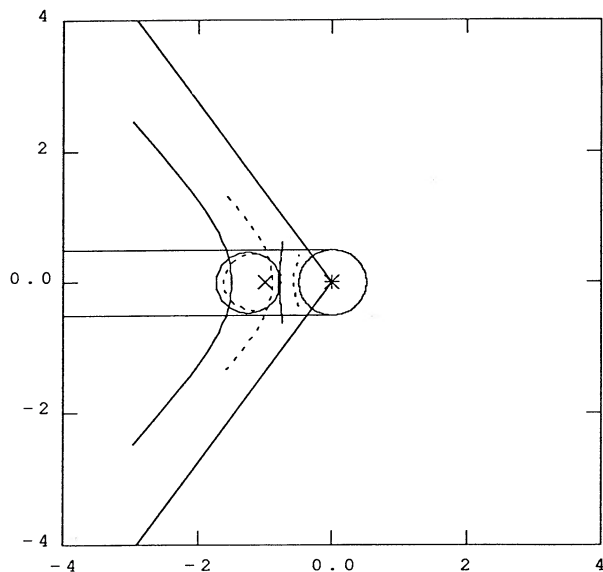


FIG. 5.—Schematic depiction of the ionization cavity surrounding the neutron star. View is looking down on the orbital plane of the binary. The location of the neutron star is marked by a cross ($\times$), while the location of the O star is marked by an asterisk. Unit of distance is the stellar separation a . The solid curve surrounding the neutron star is the boundary described by the ionization parameter $q_x = 8.0$. Isovelocity contours of -780 and -1400 km s^{-1} are shown for the case of $\beta = 1.0$ (solid curves) and 0.5 (dashed curves). Note for comparison that the ionization boundary with $q_x = 8$ for $\beta = 0.5$ nearly coincides with the $q_x = 8.0$, $\beta = 1$ boundary in real space but not in velocity space.

et al. In this case, the calculated column density is lower than observed. Since $n(r_z) \propto \dot{M}/V_\infty$, a higher mass-loss rate is needed to compensate for the higher terminal velocity. Similarly, the dotted line shows the variation of N_H with ϕ based on our system and wind parameters except that $\beta = 0.34$, which is the value derived by Haberl *et al.* In this case, the wind accelerates too quickly and hence, does not provide sufficient absorption in the inner wind to match the observed column densities. We conclude that only one set of system and wind parameters, namely, $a = 2.0R_O$, $V_\infty = 2100$ km s^{-1} , and $\beta = 1.0$, can repro-

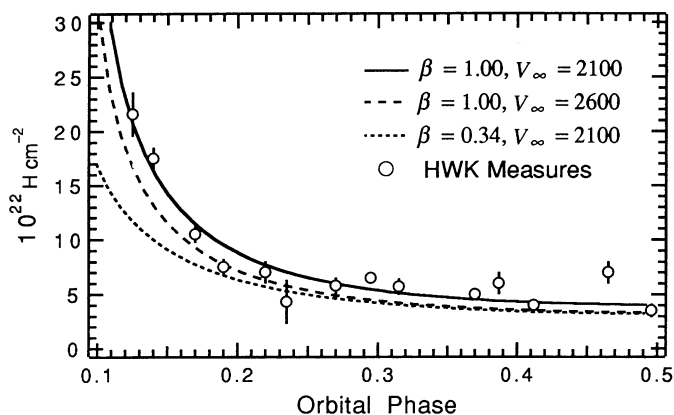


FIG. 6.—Variation of overlying wind column density with phase. Solid line: Calculation assuming $\beta = 1$, with the system parameters listed in Table 2, with $V_\infty = 2100$ km s^{-1} (as assumed by HWK) and $\dot{M} = 6 \times 10^{-6} M_\odot \text{ yr}^{-1}$. Dashed line: $\beta = 1$, with $V_\infty = 2600$ km s^{-1} (as assumed by HWK), and $\dot{M} = 6 \times 10^{-6} M_\odot \text{ yr}^{-1}$. Dotted line: $\beta = 0.34$ (as derived by HWK), with $V_\infty = 2100$ km s^{-1} and $\dot{M} = 6 \times 10^{-6} M_\odot \text{ yr}^{-1}$. Measured values are taken from Fig. 8 in HWK.

duce both the observed phase changes in the UV wind lines and the observed phase dependence of the wind column density to the neutron star.

5. EVOLUTIONARY HISTORY AND STATUS

Our revised mass for the Of star has a significant effect on the interpretation of the system's history. If the present mass of the Of star is near $50 M_\odot$, then the mass of the progenitor of the neutron star must have been $40 M_\odot$ or more, and the evolution of the system must have proceeded along the following lines (Vanbeveren 1982):

1. The system began as a binary composed of two O stars. The progenitor of the neutron star (hereafter called the primary) was more massive than its companion (the progenitor of HD 153919, hereafter called the secondary). A moderate amount of matter was lost from the system via winds from both stars.

2. When the primary evolved off the main sequence, it began RLOF (case B evolution), which lasted $\sim 10^4$ yr or so. Some of the matter lost by the primary during this epoch was transferred to the secondary, with the remainder lost from the system.

3. By the time the primary began burning helium in its core, most of its hydrogen-rich outer layers had been stripped bare by RLOF, and it appeared as a Wolf-Rayet (W-R) star with an intense wind.

4. The primary exploded as a supernova while the secondary (HD 153919) was still on the main sequence. Although a substantial amount of matter was lost in the explosion, the binary remained bound due to the large mass of the secondary.

5. The secondary evolved normally off the main sequence, now appearing as an Of star. The system started to produce X-rays due to the accretion of stellar wind material by the collapsed remnant of the primary.

A consistent picture of the evolutionary history of this system emerges if we suppose that the initial mass of the primary was near $80 M_\odot$, and the mass of the secondary was $\sim 50 M_\odot$. After 2.6×10^6 yr, the primary would have evolved off the main sequence, and its mass would have dropped down to $68 M_\odot$ due to mass-loss, while the mass of the secondary would have decreased to $46 M_\odot$. The primary then began RLOF, losing about half of its mass in 10^4 yr. If some of the mass lost (say $6 M_\odot$) were transferred to the secondary, and the rest were lost from the system, then the mass of the primary at the end of RLOF would then have been $42 M_\odot$, while the mass of the secondary would have been $52 M_\odot$. Sometime thereafter, the primary completed its nuclear burning and exploded as a supernova before the secondary evolved off the main sequence.

We can date the time of the supernova explosion by the fact that the orbit is now circular (Aslanov & Cherepashchuk 1982 and references therein; this study). According to Press, Wiita, & Smarr (1975), the circularization time scale for 4U 1700–37 is $\sim 10^6$ yr, so the supernova explosion that produced the neutron star must have occurred more than 10^6 yr ago. The time scale for HD 153919 to evolve off the main sequence to become an O supergiant is also on the order of a few million years (Maeder & Meynet 1989). Thus, the nuclear and dynamical time scales are consistent with each other.

Right after the explosion, the surviving star (HD 153919) should have revolved in an eccentric orbit, asynchronous with its rotation (Wheeler, McKee, & Lecar 1974). Later, the orbit

would tend to become circular and synchronous, if the star were tidally distorted (Press, Wiita, & Smarr 1975). Is HD 153919 tidally distorted? The strongest evidence of tidal distortion is the broad-band light curve of the system which shows a $\sim 6\%$ variation (Heap 1973; Penny et al. 1973; van Paradijs et al. 1984). The photometric variations are usually interpreted to mean that HD 153919 is distorted by tidal interactions with the neutron star, although the light curve is complicated and not easily modeled (van Paradijs et al. 1978). However, the system parameters derived in § 3 imply that the height of the tidal bulge (Lecar, Wheeler, & McKee 1976), $h = M_x/M_O(R_O/a)^3$ for a circular orbit, is only $4 \times 10^{-3} R_O$, which is not enough to have a significant effect on the light curve. Also, a large tidal deformation would give rise to phase-dependent mass-loss (Friend & Castor 1982), which should manifest itself as a phase-dependent velocity gradient (Hutchings 1976). The velocity gradient (Fig. 2c) shows only a very slight variation with phase. On the other hand, there is a problem in explaining the observed light variations if the tidal distortion of the O star is so small. X-ray heating of the O star's photosphere appears to be insufficient. The amount of heating needed to cause the observed variations in optical brightness is much larger than could be produced by X-radiation if $L_x/L_O = 10^{-3}$. The complicated and variable nature of the light curve is still to be explained.

Whether the orbit first becomes circular or synchronous depends on the ratio of the circularization to synchronization time scales (Press et al. 1975):

$$\frac{\tau_{\text{circ}}}{\tau_{\text{synch}}} \sim 1.54 \frac{P_{\text{rot}}}{P_{\text{orb}}} \alpha_I^{-1} (1 - e_i^2)^{1/2} \left(\frac{a}{R_O} \right)^2 \frac{M_x}{(M_O + M_x)} \quad (9)$$

where P_{rot} is the rotational period of the O star, e_i the initial eccentricity immediately after the supernova explosion, and α_I a constant describing the moment of inertia of the O star. If the initial eccentricity right after the SN explosion were less than 0.94, our revised system parameters and $\alpha_I \sim 0.2$ imply that the orbit of 4U 1700–37 would have become synchronous before it became circular. Since the orbit is now nearly circular, this would argue that the Of star should be rotating at the synchronous velocity (300 km s^{-1}). In fact, the equatorial rotation velocity is only half that (Wolff & Morrison 1974), if the effect

of gravity darkening on the widths of photospheric absorption lines is not taken into account. If the nonsynchronous rotation rate turns out to be real, then this may be evidence that the initial eccentricity was near 1.0, i.e., that the system was nearly disrupted by the supernova event.

6. CONCLUSIONS

HD 153919 need not be as undermassive as previous analyses suggest if the X-ray optical depth of the inner wind is nonnegligible. In particular, we find that the wind terminal velocity, the location of the Of star in the H-R diagram, the V_∞ - V_{esc} ratio, the wind acceleration, and the evolution of the binary system are more easily understood in terms of modern theories of stellar atmospheres and massive binary evolution. The progenitor of the neutron star probably was more massive than $40 M_\odot$, and thus the total system mass was probably 70 – $80 M_\odot$ or larger.

The wind of HD 153919 is similar to winds from single Of stars in two important respects: the wind acceleration is described by $\beta \sim 1.0$; and the ratio of terminal velocity to escape velocity is ~ 3 . Thus, the gross properties of the wind are similar to those of single star winds. However, we emphasize that the validity of these conclusions depends on a firm knowledge of the duration of the X-ray eclipse, since an uncertainty of 15° in θ_E can translate into an uncertainty of 50% in the radius of the OB star and a factor of 4 uncertainty in the surface gravity and luminosity. Firm knowledge of the duration of X-ray eclipse can only come from observations of the hard (50–100 keV) X-ray flux from these systems.

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