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SPECTRUM VARIATIONS OF THE X-RAY BINARY HD 153919 = 3U 1700–37

G. G. FAHLMAN,* R. G. CARLBERG, AND G. A. H. WALKER*
Institute of Astronomy and Space Science, University of British Columbia
Department of Geophysics and Astronomy, 2075 Westbrook Mall, Vancouver, B.C., Canada, V6T 1W5
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ABSTRACT

We discuss some recent spectroscopic observations of the Of star HD 153919, the primary in the 3U 1700−37 X-ray binary system. Two distinct variable components are present in the He I λ5876 P Cygni line and in the strong Hα emission line. One component is displaced by 400–600 km s^{-1} to the red. It has not been noted previously and may only be a fluctuation in the emission envelope. The other component, with a radial velocity of roughly 800 km s^{-1}, appears to be a phase-dependent absorption feature. Some implications of interpreting this feature as absorption by an extended wake trailing the secondary are discussed. In particular, if we identify the radial velocity of the wake feature with the terminal velocity of the stellar wind, then, depending on the mass loss rate of the primary, the system should emit a flux density at 3 cm in the range between 2–13 mJy.

Subject headings: X-rays: binaries — stars: Of-type — stars: individual

I. INTRODUCTION

The bright Of star HD 153919 has been identified as the primary star in the eclipsing binary system 3U 1700−37 (Jones *et al.* 1973; Penny *et al.* 1973). The optical spectrum of the system has been extensively studied (Hensberge, van den Heuvel, and Paes de Barros 1973; Wolff and Morrison 1974; Bessell *et al.* 1974; Hutchings 1974; Conti and Cowley 1975; Dachs 1976,) and a summary of its physical characteristics has been given by Hutchings (1976*a*). The period is $3^{d}412$ and the component separation is 2×10^{14} cm, which corresponds to 1.4 R_p, where the radius of the primary $R_p \approx 20\, R_{\odot}$.

Apart from the X-ray emission, the most interesting aspect of this system is that the secondary, presumably a neutron star, is moving supersonically through the dense stellar wind of the Of primary. An extended wake is expected to trail the secondary (Hensberge, van den Heuvel, and Paes de Barros 1973; Hutchings 1974) and may be responsible for some of the anomalies in the X-ray and optical observations. The asymmetry in the X-ray light curve observed by Mason, Branduardi, and Sanford (1967*a*, *b*) indicates a concentration of material behind the secondary which would be the wake, although this evidence is not particularly compelling. Optical spectra obtained by Conti and Cowley (1975) show an extra absorption feature with a velocity of about −600 km s^{-1} in the P Cygni profile of the He I λ5876 at phases near 0.7. They suggest that it is caused by the wake seen against the primary. Walker (1976) and Dachs (1976) have also noted this feature. Conti and Cowley (1975) also suggest that a similar absorption appears in the Hα profile at the same phase.

In 1976 August we obtained a number of high-quality spectra of HD 153919 in 5600–6900 Å region. Variable components are present in both the Hα and He I λ5876 profiles which are qualitatively similar to those seen by Conti and Cowley (1975) but are visible over a more extended phase interval in our data. We will discuss these observations and their possible relationship to the wake in this *Letter*.

* Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS

Our spectra were obtained with the 2.1 m telescope of the Kitt Peak National Observatory using the white spectrograph and a linear array of 1024 silicon diodes (Reticon Corporation) as the detector. A full description of the system has been given elsewhere (Buchholz *et al.* 1976; Walker *et al.* 1976). The observations are listed in Table 1. The individual records indicated were averaged to produce the spectra shown in subsequent plots. In view of the low declination of HD 153919, the observations were made through a considerable air mass (sec z ≈ 3), and telluric water vapor features are present in all the spectra. The approximate linear scale at the Reticon is 1.37 Å per diode. Each spectrum was smoothed

TABLE 1

SPECTROSCOPIC OBSERVATIONS

Data File	JD* (2,442,000+)	Phase†	Exposure Time‡ (seconds)	Number of Records
F4..........	994.665	0.738	281	3
F6..........	994.675	0.741	281	1
F44..........	996.650	0.319	240	3
F46..........	996.668	0.325	240	4
F97..........	997.644	0.611	250	0
F99..........	997.662	0.616	100	12
F101.........	997.683	0.622	100	18
F158.........	998.710	0.923	300	4

* Mid-exposure of all records.
† Phase computed with $P = 3^{d}4126$, $T = 2{,}441{,}787^{d}500$.
‡ For a single record.

by a low pass filter with a cutoff at 75% of the Nyquist frequency and rectified by fitting a third or fifth order polynomial through selected continuum points. The wavelength scale was established by the dispersion curves for He-Ne-Ar comparison spectra obtained on each night. However, the zero point of the wavelength scale is not fixed, and in practice the stellar spectra were aligned so that the average velocity of the interstellar lines at λλ5780 and 5890 (D_2) was zero.

III. RESULTS

Figure 1 shows the filtered and rectified data in the regions around Hα and He I λ5876. Apart from the phase-dependent features discussed below, there are no other obvious spectral variations evident over the orbital cycle covered by our data. In this respect, HD 153919 differs from HDE 226868/Cyg X-1 and HD 77581/3U 0900−40 in which marked changes in the spectrum occur over a single cycle (see, e.g., Hutchings *et al.* 1974; Zuiderwijk, van den Heuvel, and Hensberge 1974).

The asymmetrical appearance of the Hα emission profile, its equivalent width of 13.8 Å (in F44), and its peak radial velocity of ~100 km s^{-1} are all consistent with the data of Conti and Cowley (1975). The absorption feature at λ6527 which gives the Hα emission profile a P Cygni type appearance, is likely due to He II (5–14). This identification is consistent with the strength of other members of the He II (5–n) series which are present in our spectra.

The P Cygni profile of the He I λ5876 is remarkable. The emission component appears to be double with a distinct minimum occurring at a constant velocity of 310 km s^{-1}. The relative strengths of the two emission peaks vary. The absorption component has an extensive violet wing and appears to be double except in F44 and F46 (at phases near 0.32). This structure is not seen in the C III λ5696 emission which appears to be very steady in strength and velocity.

In order to study the variability in more detail, we substracted F44 from the other spectra. The resulting difference spectra are sensitive to differences in the wind structure preceding and following the secondary and are shown in Figure 2.

There are two prominent and relatively narrow features which appear in both Hα and λ5876 at all three phases following X-ray source passage. The blue feature, with FWHM at Hα of ~220 km s^{-1}, appears to correspond to the anomalous absorption in λ5876 commented on by Conti and Cowley (1975) and Dachs (1976). In our spectra, it is very clearly present in Hα as well as λ5876 with virtually identical width and depth, although its strength is only half that seen by Conti and Cowley (1975). The red feature, which does not seem to have been noticed before, has a FWHM at Hα of ~320 km s^{-1} and a constant central depth. The variation on the blue side of this component at Hα is due to a separate variation in the peak intensity of Hα. This causes the apparent doubling of the profile in F158. The Hα emission is weaker during X-ray eclipse, which agrees with the results of Conti and Cowley but is contrary to the variation discussed by Dachs (1976). Some care must be taken in interpreting this result because of contamination by telluric water vapor. From a comparison of the strength of the easily identified feature at λ6519, it seems unlikely that telluric water vapor alone could cause the observed effect. At λ5876 the red feature is considerably weaker than at Hα and the profile is not as well defined.

There is also an apparent broad positive feature between the two negative features at λ5876. This must be regarded with some caution because our difference technique is sensitive to changes in the stellar continuum. The mean light curve of HD 153919 has a range of $\Delta V \approx$ 0.06 mag (Penny *et al.* 1973) with considerable scatter (Bolton and Herbst 1976), and it is not possible to predict with certainty the relative continuum level variation expected in our data. If the continuum changes by $\Delta I/I$ between F44 and any of the other spectra, the relative emission profile $P(\lambda)$ will appear in the difference with a strength $P(\lambda)\cdot(\Delta I/I)$.

The measured radial velocities of the red and blue difference features are given in Table 2 and are accurate to ± 70 km s^{-1} although the values for F158 are particularly uncertain because of blending with telluric lines. We note the following points: (1) The blue component may have a variable velocity around a mean of -800 km s^{-1}. This velocity is significantly greater than that reported by Conti and Cowley (1975). An important result is that the velocity does not move steadily toward the blue as phase increases, contrary to the suggestion of Conti and Cowley. Clearly any firm conclusion on phase-dependent motion would require much more extensive data. (2) The interpretation of the red component is ambiguous. It may be due to an extra emission component in F44 and F46, or it may be an absorption which occurs in the other data. The limited velocity measurements in Table 2 suggest that, in λ5876 at least, it is an absorption which occurs together with the blue component discussed above. (3) The variation of the peak intensity of Hα has definitely distorted the velocity measurement of the red feature at Hα in F158 and may also have affected the velocity of this feature in F97, F99, and F101.

IV. DISCUSSION

The appearance of a strong absorption component with a redshift of 400–600 km s^{-1} in a system with a strong stellar wind is puzzling. If it is a true absorption,

TABLE 2

RADIAL VELOCITIES OF THE DIFFERENCE FEATURES

Data File	Phase	Hα (km s^{-1}) Blue	Hα (km s^{-1}) Red	He I λ5876 (km s^{-1}) Blue	He I λ5876 (km s^{-1}) Red
97....	0.611	−720	450	−840	560
99....	0.616	−750	450	−730	600
101...	0.622	−770	430	−790	600
4.....	0.738	−870	420	−900	460
6.....	0.741	−880	420	−930	440
158...	0.923	−740	330	−740	510

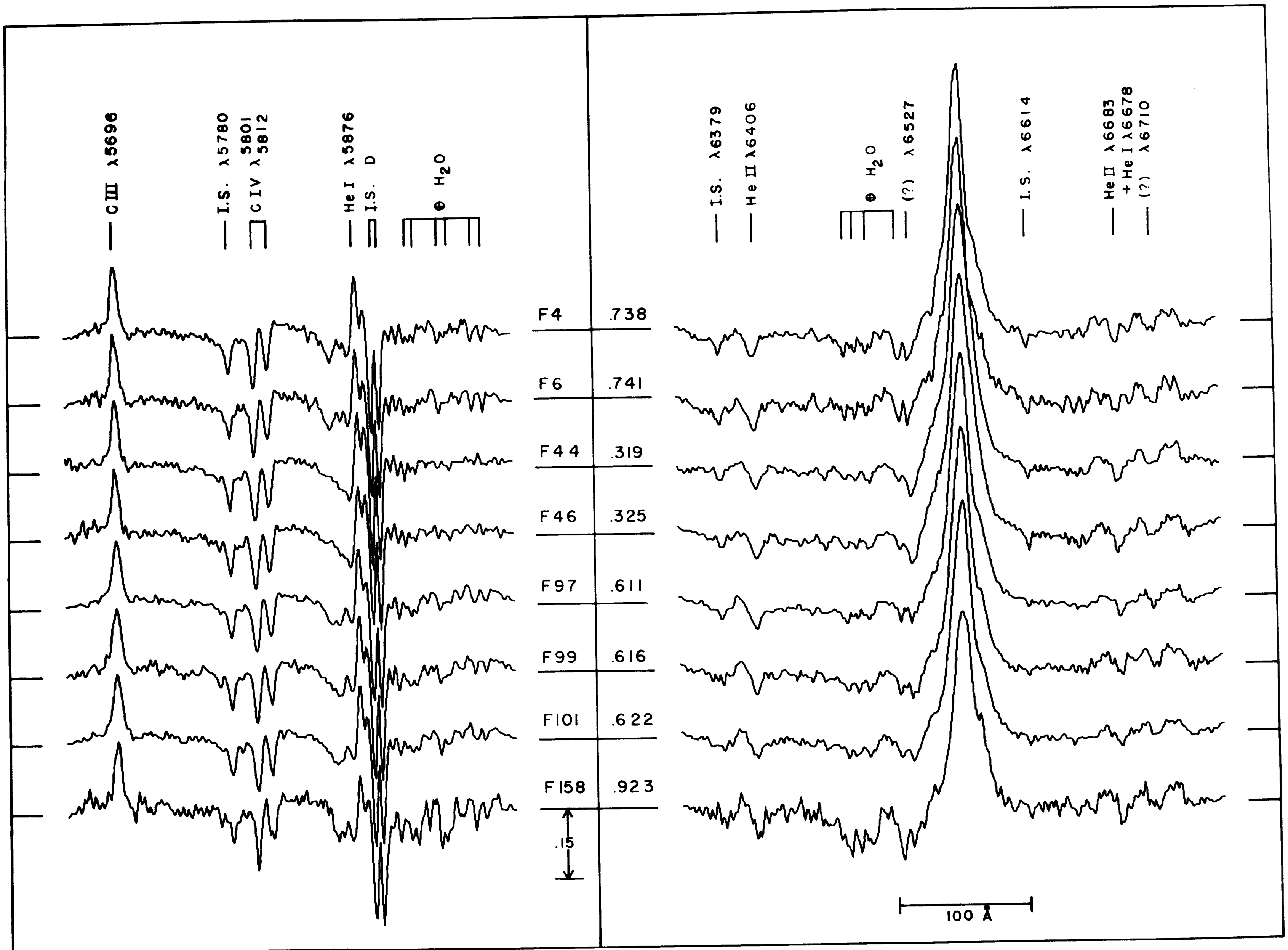

FIG. 1.—The filtered and rectified spectra are shown near He I λ5876 (*left*) and Hα (*right*). The spectra are labeled by the observation number and phase listed in Table 1. Note that the questioned λ6527 feature is almost certainly due to He II.

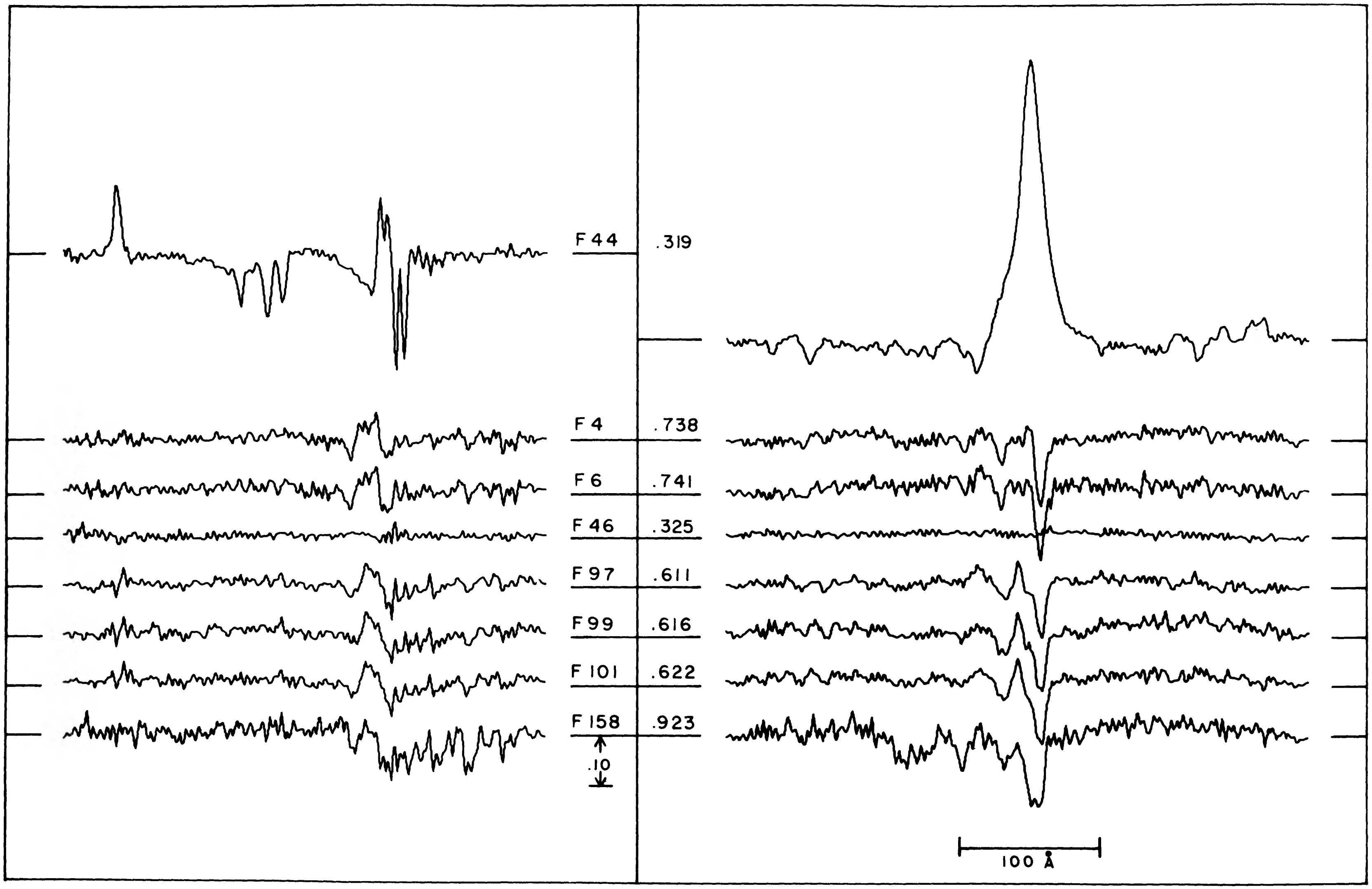

Fig. 2.—The difference spectra (FX-F44) are shown below the F44 spectrum. The difference for F46 gives an indication of the sensitivity of the technique. The variations at the He I λ5876 and Hα are discussed in detail in the text.

it cannot be easily associated with matter falling into the secondary because it is visible during eclipse. In view of our limited data, the possibility of a transient feature in F44 and F46 cannot be ruled out. Further observations would settle this issue.

The variation in the peak intensity of Hα is also somewhat anomalous. As Dachs (1976) pointed out, the X-ray source will heat a region around it, extending out to, say, 10^{12} cm for densities near 10^{11} cm^{-3}, and this hot volume of gas will be a less efficient source of Hα photons than the undisturbed stellar wind (Hatchett, Buff, and McCray 1976). Consequently, one would expect Hα to be weaker at X-ray source passage and stronger at eclipse whereas just the opposite seems to be the case. The Hα variation could perhaps be tied to the anomalous absorption in the X-ray light curve as the secondary approaches eclipse (Mason, Branduardi, and Sanford 1976*a*, *b*). Both observations seem to be consistent with a modest ($\sim$3 times) density enhancement in the stellar wind lagging behind the secondary perhaps being caused by the gravitational pull of the secondary. The X-ray heated gas might be seen best at phases just preceding X-ray source passage; and, according to the calculations of Hatchett, Buff, and McCray, one would expect the variation in the Hα to be correlated with a variation in N III λ4640.

The blue absorption component has been observed for a number of years and must therefore be associated with a relatively permanent physical structure in the binary system. Some implications of attributing the absorption to a cold ($T \approx 10^4$ K) wake are discussed below. (1) If we assume a constant velocity of -800 km s^{-1} for the wake, then from phases $\phi = 0.62$ to $\phi = 0.93$, it will move outward a radial distance of 7.3×10^{12} cm. The lack of marked changes in the strength or width of the absorption implies that the physical properties of the wake remain more or less constant over a distance along the wake of $\sim 1.5 \times 10^{13}$ cm. The wake, however, must disappear somewhere between $\phi = 0.94$ and $\phi = 0.32$ because it is not seen in F44 and F46. (2) To be seen as an absorption, the wake must be cooler than the photosphere of the primary. A cold narrow wake can have densities consistent with an absorption of the strength observed (Carlberg 1977), but the line width cannot be due to thermal broadening. The wake is expected to be turbulent, but the velocities expected are smaller than required to account for the line width and should decrease down the wake (Carlberg 1977). (3) The wake is not being accelerated outward and therefore we conclude that the terminal wind velocity of HD 153919 is $v_\infty \approx 800$ km s^{-1}. (This would mean that Hα is not a P Cygni profile.) The velocity excitation relationship discussed by Hutchings (1974) suggests a slowly accelerating wind in the region where the optical features are formed. If the terminal velocity is reached in the vicinity of the secondary, the accretion wake should point at an angle of $\theta \approx 13°$–$20°$ relative to the line of centers. Consequently, an absorption dip in the X-ray light curve is expected at phases $\phi =$ 0.54–0.57. A clear identification of such a dip in the available data (Jones *et al.* 1973; Mason, Branduardi, and Sanford 1976*a*, *b*) is not possible because of the high level of intrinsic variability. A terminal velocity of $\sim$800 km s^{-1} is consistent with the (mean velocity, mass loss rate)-relationship for early-type supergiants found by Hutchings (1976*b*) provided $\dot{M} \gtrsim 10^{-5}\ M_\odot$ yr^{-1}. The much higher terminal velocity of $\widetilde{2}700$ km s^{-1} suggested by de Freitas Pacheco (1976) is inconsistent with the relationship if $\dot{M} \approx 1.5 \times 10^{-5}\ M_\odot$ yr^{-1}.

The wind parameters would be usefully constrained by appropriate radio (and perhaps infrared) observations. Using the equations presented by Wright and Barlow (1975) with a distance of 1.7 kpc (Bolton and Herbst 1976) and the value $v_\infty \approx 800$ km s^{-1}, we estimate the flux density at 3 cm to be a potentially observable 13 mJy for the mass loss rate $\dot{M} = 1.5 \times 10^{-5}\ M_\odot$ yr^{-1} suggested by Hutchings (1976*c*). However, at that rate, the predicted X-ray luminosity is $L_x = 2.4 \times 10^{37}$ ergs s^{-1} which is at least a factor of 4 larger than observed (Jones *et al.* 1973; Mason, Branduardi and Sanford 1976*a*, *b*). Consequently $\dot{M}$ may be overestimated by that factor and, since $S_\nu \propto \nu^{0.6} (\dot{M}/v_\infty)^{4/3}$, S_ν (3 cm) may be only 2 mJy.

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