THE ASTROPHYSICAL JOURNAL, 432:770–784, 1994 September 10

A STUDY OF THE MODERATELY WIDE WOLF-RAYET SPECTROSCOPIC BINARY HD 190918

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Received 1993 October 29; accepted 1994 March 9

ABSTRACT

Radial-velocity observations of the Wolf-Rayet spectroscopic binary HD 190918 obtained from 25 spectrograms covering the yellow-green range are presented. In general three absorption lines were measured to determine the line-of-sight motion of the O star and one unblended emission line, He II λ5411.52, for the Wolf-Rayet star. A sharp C III λ5696 emission line, as seen in most Of type spectra, was detected on each spectrogram and measured. This line follows the predicted radial-velocity curve of the O star fairly well when the radial velocities are shifted by an appropriate amount.

New orbital elements have been found for the O star, for the Wolf-Rayet star, and for the C III emission line, see Table 3. The estimated systemic velocity is -20.9 ± 0.7 km s^{-1} for the O star, $+70.1 \pm 4.6$ km s^{-1} for the Wolf-Rayet star, and -34.2 ± 1.5 km s^{-1} for the sharp C III emission line. The systemic velocity of the O star is reasonable considering the expected line-of-sight component of motion due to the peculiar motion of Population I stars, Galactic rotation, and reflex solar motion. We adopt the O-star systemic velocity as a fiducial radial velocity for the binary HD 190918. This shows that the He II λ5411 line of the WN4.5 star is displaced longward by 91.1 km s^{-1}, while the sharp C III line appears to be formed in a body of gas moving toward the observer by an additional 13.3 km s^{-1}.

The positive displacement of He II λ5411 is real; it indicates systematic motion of the plasma forming the He II lines relative to the line-of-sight motion of the center of mass of the binary system. We suggest that He^{++} ions are falling into the line-emitting region of the Wolf-Rayet star from a remnant of the material from which the star is formed. In the case of HD 190918 the Wolf-Rayet star appears to pass through periastron 10.0 days (0.09 in phase) before the O star does. This may indicate that a density enhancement in the line-emitting region of the Wolf-Rayet star reaches periastron before the center of mass of the Wolf-Rayet star reaches its closest point opposite the O star.

Consideration of the size of the orbit, the known size range of O and Wolf-Rayet stars, and the minimum masses of the stars indicates that an internally consistent model is obtained when $i = 25°$ or $i = 20°$. In the first case the companion is a main-sequence O star, in the second it is an O-type supergiant. We discuss the implications of each possible solution including the swath traversed by the O star in the outer part of the line-emitting region of the Wolf-Rayet star and the possible generation of X-rays. We conclude that our observations of the sharp C III λ5696 emission line confirm the hydrodynamic models of Stevens, Blondin, and Pollock which show that extensive, chaotic tongues of cooling plasma are formed perpendicular to the line joining the stars in the case of colliding winds in massive binary systems. We describe observational tests which may be used to confirm what type of model is best for the line-emitting region of a Wolf-Rayet star.

Subject headings: binaries: spectroscopic — stars: individual (HD 190918) — stars: Wolf-Rayet

1. INTRODUCTION

We report radial-velocity observations of the Wolf-Rayet spectroscopic binary HD 190918 = WR 133, spectral type WN4.5 + O9.5 Ia obtained in the years 1986 to 1992. The WR number and the listed spectral type are from the catalog by van der Hucht et al. (1988). Twenty-five spectrograms obtained in the yellow-green region are used to study the radial-velocity changes of the stars of HD 190918.

The O star of HD 190918 follows the radial-velocity curve predicted from the unpublished orbital elements of Fraquelli, Bolton, & Horn (1983) quite well. We have used these preliminary elements and our observations of the radial velocity of the O star to obtain a set of definitive orbital elements for the O star of HD 190918. Our solutions for orbital elements (see Table 3 below were made using the program RVORBIT developed by Graham Hill at the Dominion Astrophysical Observatory. The O-star values of P, e, and ω were adopted for the Wolf-Rayet star and a solution was made for T_{peri}, K, and γ for the Wolf-Rayet star. The radial velocities determined from the weak, sharp C III λ5696 emission line (a line typical of an O-type supergiant) follow the radial-velocity curve for the O star fairly well but the γ-velocity is different from that of the O star. The implications of these results are discussed in § 3.

2. THE OBSERVATIONS

2.1. *The Spectrograms*

Twenty-five spectrograms of HD 190918 were recorded with a 30 mm, liquid nitrogen-cooled, bare EG&G RL1872F/30 Reticon with a diode size of 15 μm at the focus of the Casse-

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grain spectrograph of the 1.83 m telescope of the Dominion Astrophysical Observatory. The nominal dispersion is 30 Å mm^{-1} with a three-pixel resolution element of about 1.44 Å. The spectrograms were obtained in the yellow-green spectral region from about 5150 Å to about 6000 Å. Sufficient dark and flat-field lamp exposures were obtained to allow correction for pixel-to-pixel sensitivity differences and to remove most systematic noise.

A log of the spectra obtained is presented in Table 1. The moment of mid-exposure is reported in the third column as a Barycentric Julian Day (BJD). The mean heliocentric radial velocities found from the two interstellar Na I lines together with their associated 1 σ values are listed in the fourth and fifth columns. The phase in the orbit of the O star at which the spectrogram was obtained is noted in the sixth column of Table 1. That for the Wolf-Rayet star is listed in the seventh column. (These phases have been calculated using the period and the times of periastron passage given in Table 3 below.)

Comparison spectra were obtained before and after each stellar exposure with the telescope pointing at the target star. An Ar-Fe source was used. The wavelength scale was fitted using a fifth-order polynomial which typically yielded a standard error for one wavelength of ± 0.020 Å. Most exposures were of the order of 1 hour; none exceeded 2 hours. Consequently there were few cosmic-ray hits on the spectra and the flexure shifts, if any, were removed effectively by using the wavelength scale resulting from the average of the arc exposures before and after the stellar exposure. No observations were obtained at hour angles exceeding ± 2.5 hours.

A typical yellow-green spectrogram obtained on 1991 November 28 UT is shown in Figure 1. This spectral region yields the best unblended emission lines for finding the radial

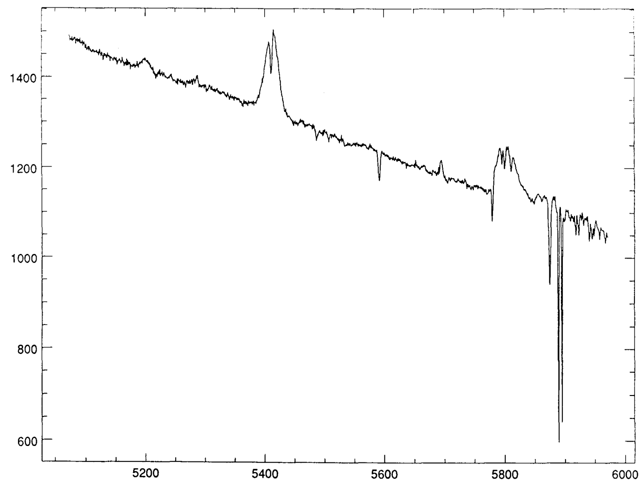

FIG. 1.—Spectrum of HD 190918 on BJD 2448588.574. The interstellar Na I lines at the right hand end of the spectrum show the resolution of the spectrograph. The ordinate gives ADC units, the abscissa the wavelength in angstrom units.

velocities of Wolf-Rayet stars. It is desirable to select features for measurement which can be attributed to a single emission line so that one can assign a laboratory wavelength in angstroms and find the radial velocity of the Wolf-Rayet star on an absolute scale.

While our work was in progress, we became aware of an intermittent instrumental problem with the Cassegrain spectrograph which, from time to time, generates a small shift of the zero point of the wavelength scale of the comparison spectrum from that of the stellar spectrum. The scale of the spectrograms

TABLE 1

LOG OF SPECTROSCOPIC OBSERVATIONS OF HD 190918

Observation Number	UT Date	BJD − 2440000.0	NaI[a] (km s^{-1})	σ_{NaI}[b] (km s^{-1})	Phase[c] (cycles)	Phase[d] (cycles)
1	1986 Aug 15	6657.782	−27.2	6.5	0.214	0.303
2	1987 Aug 18	7025.834	0.6	0.1	0.489	0.578
3	1987 Sep 10	7048.775	−2.0	4.2	0.693	0.782
4	1987 Sep 12	7050.752	−6.8	4.4	0.710	0.799
5	1987 Oct 15	7083.607	20.8	5.8	0.003	0.092
6	1987 Oct 16	7084.698	18.1	7.2	0.012	0.101
7	1988 Jul 22	7364.752	−12.5	0.0	0.504	0.593
8	1988 Jul 23	7365.734	−13.6	0.1	0.513	0.602
9	1988 Jul 26	7368.723	−14.2	3.1	0.539	0.628
10	1988 Aug 18	7391.757	−3.6	1.1	0.744	0.833
11	1988 Aug 26	7399.701	−4.8	3.4	0.815	0.904
12	1988 Aug 27	7400.692	−10.5	2.1	0.824	0.913
13	1988 Sep 26	7430.644	−8.8	9.6	0.090	0.179
14	1990 Aug 10	8113.958	−6.8	0.0	0.170	0.259
15	1990 Aug 11	8114.989	−13.3	0.0	0.179	0.268
16	1990 Aug 16	8116.965	−12.6	0.1	0.196	0.285
17	1990 Aug 28	8131.701	−11.2	1.8	0.327	0.416
18	1990 Aug 30	8133.764	−12.6	2.2	0.346	0.435
19	1991 Sep 06	8505.720	−13.9	0.1	0.655	0.744
20	1991 Sep 08	8507.895	−14.8	0.2	0.674	0.763
21	1991 Sep 09	8508.790	−11.8	0.3	0.682	0.771
22	1991 Nov 28	8588.574	−10.2	3.1	0.392	0.481
23	1991 Nov 29	8589.635	−10.3	2.3	0.402	0.491
24	1992 Sep 05	8870.680	−7.4	0.5	0.902	0.991
25	1992 Sep 06	8871.816	−7.4	0.3	0.912	0.001

[a] Mean velocity from two lines measured independently by each of us.
[b] Root mean-square deviation from the listed velocity from the independent measurements.
[c] Fraction of a cycle calculated with $P = 112.4$ days, $T_{peri} = 2447420.5$ for the O star.
[d] Fraction of a cycle calculated with $P = 112.4$ days, $T_{peri} = 2447410.5$ for the Wolf-Rayet star.

is not affected. In order to minimize the effect of the random small shifts between the comparison and the stellar spectra on our stellar radial velocities, we have corrected the zero-point of the wavelength scale of each stellar spectrogram in such a way that the observed radial velocity of the interstellar Na I lines from that spectrogram is equal to the mean value of the Na I velocities given in Table 1. This mean value is -7.9 ± 1.9 km s^{-1}. The standard deviation about this result indicates the precision of the radial velocities which may be obtained using the Cassegrain spectrograph at 30 Å mm^{-1} and measuring two sharp absorption lines formed in the gas between the observer and the star. The interstellar-line radial velocity is expected to be constant, independent of the epoch at which the observations are made.

2.2. *The Measuring Techniques*

The spectrograms of HD 190918 were measured twice, 17 (all except numbers 14, 15, 16, 19, 20, 21, 24, and 25) by Underhill, the same 17 once by Hill, and the other eight twice by Hill. Then a mean velocity displacement was found for each line and that displacement was corrected to the wavelength zero point found from the Na I interstellar velocity for that spectrogram. Underhill inspected short sections of the spectra on a computer terminal and bisected the lines; Hill used cross-correlation techniques, as described by Fahlman & Glaspey (1973), for all the spectrograms. In addition Hill measured by bisection the displacements of the lines of the eight spectrograms not measured by Underhill. He used the same process as Underhill did. The interactive language RETICENT was used to reduce and measure the spectrograms.

The cross-correlations were made relative to the spectrogram of 1991 September 6, number 19, using the procedure described by Fahlman & Glaspey (1973). In the case of the Na I lines a window 14 Å wide centered between the two lines was used; for the O III absorption line a window 7 Å wide centered on the line was used; for the He I absorption line a window 9 Å wide was used centered on the line. In all cases the window was traversed using a step of 0.04 Å. Cross-correlation was not used for the O-type absorption He II λ5411 line because it lies on top of a wide, strong Wolf-Rayet emission line and variations in the profile of this line cause variations in the background for the O star absorption line. Instead Hill measured the O star He II line by fitting a parabola to the bottom one-third of the absorption line. To determine the radial velocity of the reference spectrogram, Hill measured all of the lines by bisecting the profiles at a number of heights or depths and taking the mean result.

Heliocentric radial-velocities corrected to the wavelength zero-points indicated by the interstellar Na I lines are given in Table 2 for the O star, the Wolf-Rayet star, and for the sharp C III line. The sigma values listed for the O star velocities have been calculated from the differences from the mean velocity shown by the six estimates of radial velocity obtained from each spectrogram. In the case of the Wolf-Rayet star and the sharp C III emission line, the sigma values are the standard deviation calculated from the differences of the results obtained by cross correlation and by bisection from the mean of the two measurements. The weights for the O star radial velocities were calculated by RVORBIT from the sigma values for the O star. They are proportional to the inverse square of σ.

2.2.1. *The O Star Velocities*

The heliocentric velocity for the O star is calculated from the values of the displacements of three sharp absorption lines, He II λ5411.52, O III λ5592.37, and He I λ5875.68. The O III line appears as an absorption line in the blended continua from the

TABLE 2

HD 190918: OBSERVED RADIAL VELOCITIES FROM YELLOW-GREEN SPECTRA IN km s^{-1}

Observation Number	O Star[a]			W-R Star[b]		Sharp C III Line	
	$v_{\rm O\,Star}$	$\sigma_{\rm O\,Star}$	Weight	$v_{\rm W\text{-}R\,Star}$	$\sigma_{\rm W\text{-}R\,Star}$	$v_{\rm C\,III}$	$\sigma_{\rm C\,III}$
1	−11.1	4.6	1.64	47.6	17.8	−40.5	17.0
2	−4.2	3.1	3.62	49.2	7.9	−23.9	2.6
3	−27.6	4.0	2.17	84.4	24.4	−43.4	1.2
4	−26.7	3.4	3.01	107.7	20.3	−41.1	0.6
5	−48.8	7.6	0.60	38.3	42.5	−64.1	9.8
6	−39.6	7.3	0.65	91.2	31.3	−51.6	8.1
7	−7.7	2.5	5.56	14.7	40.0	−17.2	4.5
8	−8.7	1.2	24.15	55.7	27.3	−21.5	6.0
9	−4.6	1.8	10.73	58.7	20.8	−21.9	1.5
10	−21.8	2.4	6.04	92.2	22.8	−38.9	4.4
11	−19.0	1.9	9.63	54.2	37.8	−39.8	7.0
12	−28.6	4.1	2.07	115.6	12.2	−33.8	4.1
13	−22.3	5.7	1.07	97.4	25.4	−30.7	2.1
14	−16.4	1.4	17.74	81.5	2.8	−26.0	2.3
15	−22.0	3.7	2.54	77.0	1.5	−31.9	1.4
16	−17.8	2.2	7.18	39.0	4.2	−21.2	2.8
17	−10.9	2.6	5.14	24.1	17.5	−25.8	0.7
18	−10.3	3.4	3.01	37.6	32.6	−24.4	0.1
19	−20.9	2.9	4.13	78.9	1.5	−34.8	1.5
20	−16.6	2.1	7.89	90.3	0.3	−41.8	2.2
21	−19.9	3.2	3.40	76.8	3.5	−25.5	3.9
22	−21.8	2.6	5.14	22.8	36.3	−29.5	4.5
23	−10.3	2.4	6.04	60.3	27.4	−38.9	1.8
24	−36.3	2.5	5.56	103.6	0.3	−34.4	4.0
25	−37.2	2.0	8.69	140.7	6.1	−42.6	5.2

[a] The velocity is from three absorption lines: He II λ5411, O III λ5592, and He I λ5876.
[b] The velocity is from one emission line: He II λ5411.

two stars; the He II and He I lines are sharp absorption features lying on top of broad Wolf-Rayet emission features, see Figure 1. The O type C IV $\lambda\lambda$5801.33 and 5811.98 lines are not useful because the first blends with a diffuse interstellar band (DIB) at 5797.03 Å while the second is often difficult to decipher because of changes which occur from time to time in the underlying blend due to the Wolf-Rayet star.

2.2.2. *The Wolf-Rayet Star Velocities*

Only one emission line, He II λ5411.52, was used. This feature is broad, see Figure 1, and the central part is disturbed by the presence of the O star sharp absorption line. Underhill bisected the He II profile by finding the wavelengths of points at the same height on the steep flanks of the profile and then adopted the average wavelength from these results as the central wavelength of the line. Hill used the Fahlman-Glaspey technique with a mask that did not include the central part of the line. The mask consisted of two 11 Å wide regions on the shoulders of the line; the central 23 Å were excluded. Observation 19 was used as the reference spectrogram. In the case of the eight spectrograms not measured by Underhill, Hill measured the wavelength of the broad He II emission feature using the same procedure as Underhill.

2.2.3. *The Sharp* C III *Emission Line*

This sharp emission line at 5695.92 Å was bisected by inspection by Underhill in the case of the 17 spectrograms measured by her. Hill measured all the spectrograms by cross correlation and also measured the eight not measured by Underhill by bisection. The cross correlation was done with a mask 7 Å wide centered on the C III line relative to spectrogram number 19.

2.3. *The Orbital Elements for the Stars of* HD 190918

Solutions for orbital elements to describe the radial-velocity changes of the O star and of the Wolf-Rayet star were obtained using the computer program RVORBIT developed by Graham Hill at the Dominion Astrophysical Observatory. First a solution was obtained for the O star using the velocities and weights listed in the second and fourth columns of Table 2. We started from the set of elements for the O star derived by Fraquelli et al. (1983). We used the PDM method (Stellingwerf 1978) to check that a period near 112 days satisfied our new set of observations. We sampled a period range from 30 to 500 days. The final set of orbital elements for the O star is given in Table 3.

In the case of the Wolf-Rayet star, we solved only for T_{peri}, γ, and K, adopting the values for P, e, and ω indicated by the O star. Because the Wolf-Rayet radial velocities come from only one wide line and suffer from uncertainties which are of the order of the semi amplitude of the orbit, it is desirable to adopt values for those orbital elements which should be the same for both stars. The resulting orbital elements for the Wolf-Rayet star are given in Table 3. We tried also a solution with only P and e fixed; the results did not differ by a significant amount from the values given in Table 3, but the uncertainties for ω and T_{peri} were large, see § 3.4.

In the solution for the Wolf-Rayet orbital elements each observation was given unit weight because the range of σ-values derived from the cross-correlation and the bisection results is large. The intrinsic uncertainty of each radial velocity is of the order of ± 20 km s^{-1}. A particularly small σ-value may arise by chance; it would not be wise to weight such points highly.

Finally we solved for a set of orbital elements to represent the velocity changes of the sharp C III line, weighting each observation equally. A preliminary solution leaving the six elements unconstrained produced orbital elements which differed little from those of the O star. To obtain the adopted solution, we set P equal to the value for the O star and solved for e, ω, T_{peri}, γ, and K. The orbital elements from this solution are given in Table 3. There are too few observations near the time of periastron passage for the O star to define ω and T_{peri}, accurately.

The significance which we attach to our solutions for orbital elements is discussed in § 3. From the adopted orbital elements for the O star and the Wolf-Rayet star we derived masses and semimajor axes for the orbits as functions of inclination, i. The results are given in Table 4; they are discussed in § 3.

The radial-velocity observations and the velocity curves predicted from the elements of Table 3 are shown in Figures 2, 3, and 4. In Figure 2 the plotted error bars on the observed points

TABLE 3

ORBITAL ELEMENTS FOR HD 190918

Element	O Star[a]	W-R Star[b]	Sharp C III Line
Period (days)	112.4 ± 0.2	112.4[c]	112.4[c]
Eccentricity	0.39 ± 0.07	0.39[c]	0.65 ± 0.20
ω	198°9 ± 10°7	18°9[c]	210°4 ± 20°4
T_{peri} (BJD −2440000.0)	7420.5 ± 3.6	7410.5 ± 3.2	7422.2 ± 5.9
γ (km s^{-1})	-20.9 ± 0.7	70.2 ± 4.6	-34.2 ± 1.5
K (km s^{-1})	16.9 ± 2.1	34.4 ± 7.4	15.0 ± 3.2

[a] From three absorption lines: He II λ5411.52, O III λ5592.37, and He I λ5875.68.

[b] From one broad emission line: He II λ5411.52.

[c] Value adopted from the O-star solution.

TABLE 4

THE MASSES AND DIMENSIONS OF HD 190918

Parameter	$i = 30°$	$i = 25°$	$i = 20°$	$i = 15°$
$M_{O\ Star}$ ($M_\odot$)	6.6	10.5	20.6	47.5
$M_{W\text{-}R\ Star}$ ($M_\odot$)	3.2	5.4	10.1	22.3
$a_{O\ Star}$ ($R_\odot$)	69.1	81.7	101.1	133.5
$a_{W\text{-}R\ Star}$ ($R_\odot$)	140.6	166.4	205.6	271.7

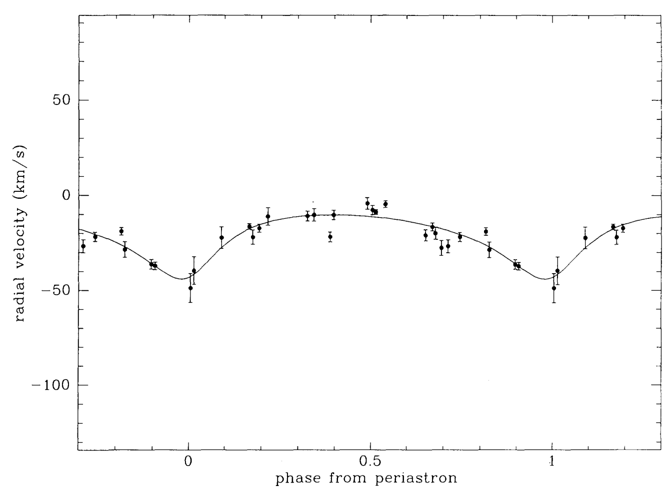

FIG. 2.—Radial-velocity curve shown by the O star. The error bars on the observed points correspond to the σ values (Table 2) associated with the observations. The time of periastron, phase 0.0, occurs at BJD 2447420.5.

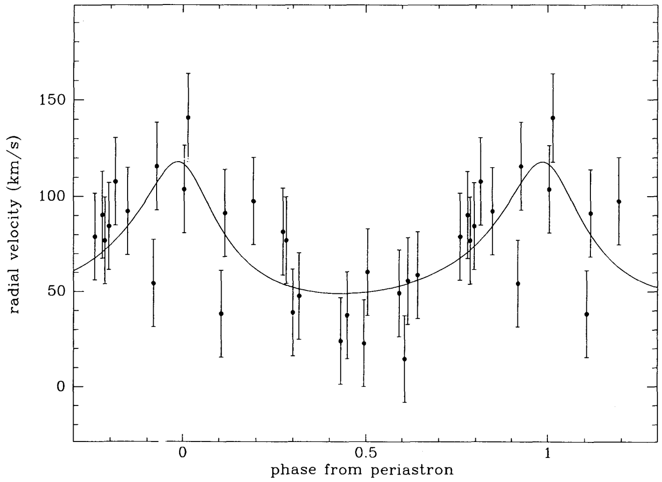

FIG. 3.—Radial-velocity curve shown by the Wolf-Rayet star. The error bars on the observed points correspond to the rms $O-C$ of the points. This is ± 22.8 km s^{-1}. The time of periastron, phase 0.0, occurs at BJD 2447410.5.

are the standard deviations (see Table 2) of the mean velocities. In Figure 3, the root-mean-square (rms) $O-C$ is used as the error bar; it is ± 22.8 km s^{-1}. In Figure 4, the error bars correspond to a rms $O-C$ value of 6.8 km s^{-1}.

3. DISCUSSION

3.1. *Precision of the Observed Radial Velocities*

As noted in § 2, each of the radial velocities given in Table 2 has been adjusted to such a wavelength zero point that the radial velocity of the interstellar Na I lines determined from that spectrogram is -7.9 km s^{-1}. The average standard deviation of the Na I velocities determined from two independent measurements of the two lines is 2.35 ± 0.52 km s^{-1}. This standard error is independent of the zero-point shift of instrumental origin noted in § 2.1. It is indicative of the precision that may be obtained when measuring two sharp absorption lines.

The average of the $\sigma_{\rm O\,Star}$ values given in Table 2 is 3.22 ± 0.32 km s^{-1}. The individual values of $\sigma_{\rm O\,Star}$ come from measuring three absorption lines (see Fig. 1) by two different methods. The results obtained on each spectrogram from each of the lines show a spread. One might suspect that using only the O III absorption line (because it occurs in a region where there are no strong Wolf-Rayet broad emission lines) would give more precise velocities for the O star than using the average from three lines, two of which fall on top of Wolf-Rayet emission lines does, but this is not so. The average $\sigma_{\rm O\,Star}$ determined from the two measurements of the O III line alone is 3.12 ± 0.59 km s^{-1}. This average value is essentially identical with that from three absorption lines but the spread about the average value is larger when only one line is used than when three lines are used.

We conclude that using the velocity displacements from three absorption lines to determine the radial velocity of the O star gives a more precise result than does using only one line. Measuring three lines by two independent methods and taking the average result helps to beat back the random errors inherent in our measuring methods. From Figure 2 we see that the radial-velocity curve of the O star is reasonably well determined.

The average $\sigma_{\rm W\text{-}R}$-value (Table 2) is 18.6 ± 2.7 km s^{-1} while the average $\sigma_{\rm C\,III}$-value is 3.97 ± 0.71 km s^{-1}. It is impossible to measure the radial-velocity displacements of the one Wolf-Rayet line precisely. Figure 3 shows that the Wolf-Rayet velocity curve is somewhat poorly determined. The velocity displacements of the sharp C III emission line are measured somewhat less accurately than are those of the O star or of the Na I interstellar absorption lines. Figure 4 shows how well the velocity curve of the C III lines is determined. The character of the line profiles of the He II and C III emission lines can be seen from Figure 1. To obtain better precision in the orbital elements will require obtaining more observations near the phase of periastron for the O star.

3.2. *The Orbital Elements for* HD 190918

The orbital elements for the O star, the Wolf-Rayet star, and the sharp C III emission line are listed in Table 3. Because the part of the O-star radial-velocity curve near periastron is not well covered, the values for e, ω, and $T_{\rm peri}$ are determined with only moderate precision. Nevertheless it is clear that the eccentricity of the orbits of the O and Wolf-Rayet stars is moderately large.

The derived value of the eccentricity depends chiefly upon the O-star velocities found from Observations 5, 6, 13, 24, and 25. The first two require large negative zero-point corrections while the last three require negligible corrections. The zero-point corrections are, respectively, -28.7, -26.0, $+0.9$, -0.5, and -0.5 km s^{-1}. The fact that Observations 13, 24, and 25, fit the O-star predicted velocity curve rather well indicates that when those zero-point corrections and the similarly derived corrections for Observations 5 and 6 are applied, the resulting set of radial velocities leads to a secure set of orbital elements.

All the zero-point corrections have been determined in the same way from the measured displacements of the interstellar Na I lines. The need for these corrections appears to be generated by a randomly occurring small misalignment of the beam of light from the comparison source such that the angle of incidence of the beam from the comparison source on the grating is not quite identical with that of the beam of star light. This error is difficult, if not impossible, to detect while one is observing. We conclude from the reasonably small scatter of the observations about the predicted velocity-curve for the O star that the zero-point corrections which we have applied to

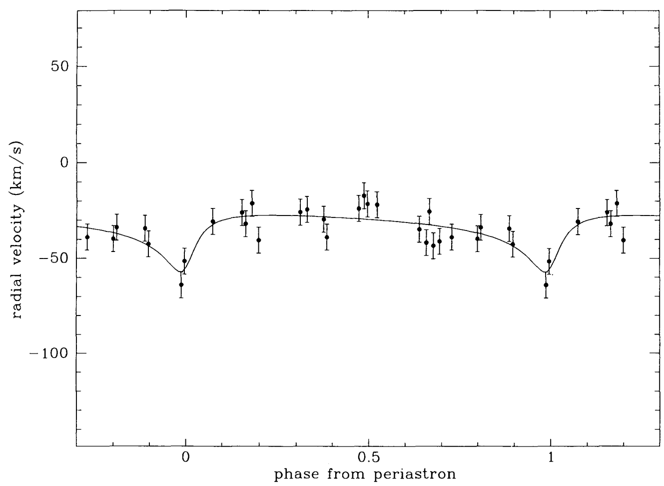

FIG. 4.—Radial-velocity curve shown by the sharp C III emission line. The error bars on the observed points correspond to the rms $O-C$ of the points. This is ± 6.8 km s^{-1}. The time of periastron, phase 0.0, occurs at BJD 2447420.5.

the wavelengths of the spectrograms correct well for this instrumental problem. Consequently we believe that the orbital elements derived for the O star are reliable.

The orbital elements for the Wolf-Rayet star are less reliable than those for the O star because of the reduced precision of the observations of the Wolf-Rayet velocity. The solution for the C III sharp emission line has about the same reliability as the O-star solution because the radial velocities determined from the C III lines have nearly the same precision as those from the O-star lines. One may question whether the displacements of the sharp C III emission line represent solely orbital motion of the plasma emitting the C III line.

Obtaining better orbital elements for the stars of HD 190918 will require concentrated observing to fill in the gaps in the phase coverage shown by our 25 observations. These observations can be planned for now that the period of HD 190918 and the time of periastron passage of the O star are known with moderate precision.

3.3. *The Systemic Velocities of the O and the Wolf-Rayet Stars*

3.3.1. *The Longward Shift of the Wolf-Rayet* He II *Lines*

The systemic velocity of the O star is -20.9 ± 0.7 km s^{-1} while that of the Wolf-Rayet star is 70.2 ± 4.6 km s^{-1}. Thus the radial velocities from He II λ5411.52 of the Wolf-Rayet spectrum are displaced 91 km s^{-1} longward of the reference wavelength set by the systemic velocity of the O star. Such longward displacements of the He II lines in Wolf-Rayet spectra have been known for a long time, see Hiltner (1945). Radial-velocity observations of V444 Cygni (Underhill, Yang, & Hill 1988a) and of CQ Cephei (Underhill, Gilroy, & Hill 1990a) show similar longward displacements of the He II lines in the Wolf-Rayet spectrum.

These displacements are intrinsic to the spectra of Wolf-Rayet stars. The He II emission lines in the spectra of the Wolf-Rayet components in HD 190918, V444 Cygni, and CQ Cephei are wide relative to the resolution of the spectrograph. The radial velocities from which the orbital solution for the Wolf-Rayet star of HD 190918 has been made have been determined by bisecting the He II line at about half height. It is the plasma which is generating the light center determined in this way which is found to be receding systematically from the observer.

Bhatia & Underhill (1988) have suggested that Wolf-Rayet emission lines are formed in a ringlike disk attached to the star by magnetically supported filaments and that the ringlike disk lies at a considerable distance (10^{13} to 10^{14} cm) from the center of the star, while Underhill & Nemec (1989) have shown that the typical shapes of Wolf-Rayet emission lines can be generated by the inclination of the disk to the plane of the sky, the speed of rotation of the disk, and the turbulence of the plasma in the disk. Additional detail about the properties of the disk as envisioned by Underhill are given in the Appendix. In the case of a binary star, the wide emission lines are shifted longward and shortward by the line-of-sight velocity changes of the star because the core of the Wolf-Rayet star drags the disk with it as it moves in its orbit. In the case of HD 190918, the full width at half maximum height of the He II lines is larger than the range in radial velocity traced out by the orbital motion of the Wolf-Rayet star.

In the case of HD 190918 one has the impression that one is seeing a complex emission line having an effective wavelength which is generated by the orbital motion of the plasma of the line-emitting region (LER) of the Wolf-Rayet star plus an intrinsic line-of-sight component of motion of the plasma. Plasma falling into the surface of the Wolf-Rayet star from the part of the LER between the observer and the surface of the Wolf-Rayet star is a likely source generating the observed longward displacement. A receding stream in the binary system seen projected against the sky seems a less likely place of origin for the longward shift because a constant longward shift of the systemic velocity of the Wolf-Rayet star appears to be seen no matter what the orientation of the binary system with respect to the observer. Radiating plasma which is part of a stream running from one of the stars around the other would show positive or negative displacements to an external observer depending on the orientation of the stream with respect to the observer at the different times of observation.

A longward shift of the He II emission lines seems to be a property of Wolf-Rayet stars rather than a property linked with the chance that the Wolf-Rayet star is a member of a binary system. Robert (1991) in her Tables 14 to 18 presents radial velocities from emission lines in the yellow-green spectral region of five Population I Wolf-Rayet stars. These radial velocities are determined from high-resolution digital spectra which were obtained in extensive series of observations made on a few consecutive nights in order to track the timewise behavior of subpeaks on the profiles of the major emission lines over intervals of 8 hours or so.

The lines observed and the method used by Robert to measure the displacements of the lines are explained in detail in Robert (1991). From her catalog of reliable radial velocities we have extracted the average radial velocity shown by the He II λ5411 line during each observing session of three to four consecutive nights.

The results are given in Table 5 together with the rms uncertainty of the average radial velocity calculated from the spread of the individual radial velocities about the mean value for the session. In Table 6 we tabulate less extensive data from the C III λ5696 emission line in the spectra of three WC stars and He I λ5876 in the WN6 stars HD 191765 and HD 192163.

The telescopes and spectrographs used to assemble the series of spectrograms measured by Robert are indicated in the last columns of Tables 5 and 6. With the CASPEC echelle spectrograph of the ESO 3.6 m telescope the detector was a CCD and the resolution was 0.07 Å per pixel. With the coudé spectrograph of the 3.6 m CFHT telescope the detector was a Reticon and the resolution was 0.10 Å per pixel. The grating spectrograph of l'Observatoire du mont Mégantic was used with the 1.6 m telescope there and the detector was a CCD giving a resolution of 1.325 Å per pixel.

It is clear that the average radial velocities shown by He II λ5411, C III λ5696, and He I λ5876 fall well outside the range ± 20 km s^{-1}. For each star, because it is a Population I object, one may estimate that the radial velocity of the star should be about $v_{gr} \pm 20$ km s^{-1}, where v_{gr} is the component of radial velocity due to Galactic rotation. We estimated v_{gr} for each star using the equation at the end of § 8.2 of Kerr & Lynden-Bell (1986) with the Galactic coordinates and distances for our five stars given by van der Hucht et al. (1988) and adopting the values for the circular velocity at the Sun and the distance to the Galactic center recommended by Kerr & Lynden-Bell. We assume that the circular velocity at the position of the stars is the same as at the Sun. The v_{gr}-values for HD 165763, HD 191765, HD 192103, HD 192163, and HD 192641 are 8.2, 9.0, 8.9, 6.9, and 7.8 km s^{-1}, respectively. Both the He II and the

TABLE 5

He II λ5411 RADIAL VELOCITIES FOR WOLF-RAYET STARS[a]

Star HD Number	Spectral Type	UT Date Observation Session	Number of Spectra	$\langle v \rangle$ (km s^{-1})	σ_m (km s^{-1})	Notes
165763	WC5	1989 Jun	28	142.9	1.0	b
191765	WN6	1987 Aug	35	158.7	2.0	c
191765	WN6	1989 Aug	8	149.8	1.0	d
192103	WC8	1989 Aug	9	108.2	0.9	d
192163	WN6	1987 Aug	26	81.1	0.7	c
192163	WN6	1989 Aug	9	70.0	1.7	d
192641	WC7+abs.	1989 Sep	2	85.2	3.0	d

[a] From Robert 1991.
[b] ESO 3.6 m telescope with CASPEC echelle spectrograph and CCD; 0.07 Å per pixel.
[c] CFHT 3.6 m telescope with coudé spectrograph and Reticon; 0.10 Å per pixel.
[d] Observatoire du mont Mégantic 1.6 m telescope with grating spectrograph and CCD; 1.325 Å per pixel.

C III line are recorded on some of Robert's spectrograms. These spectrograms yield large positive displacements for the He II λ5411 line but large negative displacements for the C III λ5696 line. Obviously these displacements do not represent motion of the center of mass of the star.

Comparison of the observed radial velocities for the five stars, given in Tables 5 and 6, with the estimated peculiar velocities of the stars shows that the He II and He I lines are displaced longward by approximately 100 km s^{-1}, while the C III line is displaced shortward by approximately 50 km s^{-1}. These results are similar to what is known from the study of spectroscopic binaries. The lines of He II and He I are longward displaced, suggesting infall, while the lines from the C^{++} ion are shortward displaced. These displacements are intrinsic to the Wolf-Rayet stars.

The displacements we have found are similar to those found by Underhill & Yang (1991) for HD 50896, WN5. Underhill & Yang suggested that the outflow velocities indicated by the lines from the C and N ions originate in outward motion of hot plasma confined to ever changing magnetically supported filaments seen projected against the face of the star. They believe that these filaments lie in the space between the surface of the star and the ringlike disk suggested by Bhatia & Underhill (1988). The filaments connect the disk to the star. Underhill et al. (1990b) have suggested that the ever changing sharp emission peaks seen on the broad Wolf-Rayet emission lines of HD 191765, some of the sharp peaks which Robert investigated, are due to plasma projected in front of the face of the star in hot ever changing filaments supported by magnetic field lines.

3.3.2. *The Distance and Peculiar Motion of* HD 190918

HD 190918 is a member of the OB association Cyg OB 3 (Humphreys 1978; Nichols-Bohlin & Fesen 1993). Nichols-Bohlin & Fesen suggest that Cyg OB 3 is at a distance of 2.3 kpc. If this distance is adopted for HD 190918, the component of radial velocity due to galactic rotation (Kerr & Lynden-Bell 1986) of HD 190918 is +10 km s^{-1} when one adopts $R_0 = 8.5$ kpc, $\Theta_0 = 222$ km s^{-1} and a flat rotation law, that is $\Theta(R)$ at HD 190918 equal to Θ_0. Because the systemic velocity of the O star of HD 190918 is −21 km s^{-1}, we infer that the peculiar component of radial velocity of HD 190918 is about −31 km s^{-1}, ignoring reflex solar motion. Such a velocity is compatible with membership in Population I and in Cyg OB 3. The predicted v_{gr} of stars in Cygnus is sensitive to the adopted rotation law for the galaxy but not to the values for r and R_0.

Using a V-magnitude of 6.70 for the small group of at least three stars which one sees on the slit head for HD 190918 (a bright central object and two "ears" indicating the presence of two fainter stars within 4 arcsec of the bright object), an extinction of 1.35 mag (Humphreys 1978 for HD 190918F), and a distance of 2.3 kpc, one finds that the visual absolute magnitude of the O and the Wolf-Rayet star together is −6.5.

When one adopts M_V-values (Conti et al. 1983) for the O star, that is −6.0 if it is an O9.5 supergiant and −4.0 if it is an O9.5 main-sequence star, one finds that the visual absolute magnitude of the Wolf-Rayet star is −5.1 or −6.3. We note in § 3.7.3 a possibility of selecting one or the other of these results by considering the X-ray flux from HD 190918. These visual

TABLE 6

C III λ5696 AND He I λ5876 RADIAL VELOCITIES FOR WR STARS[a]

Star HD Number	Spectral Type	UT Date Observation Session	Number of Spectra	$\langle v_{C III} \rangle$ (km s^{-1})	σ_m (km s^{-1})	$\langle v_{He I} \rangle$ (km s^{-1})	σ_m (km s^{-1})	Notes
165763	WC5	1989 Jun	18	−83.1	1.4	...	...	b
192103	WC8	1988 Jul	26	−32.5	0.3	...	...	c
192103	WC8	1989 Aug	9	−29.0	0.9	...	...	d
192641	WC7+abs.	1988 Jul	25	−38.3	0.9	...	...	c
192641	WC7+abs.	1989 Aug	2	−33.3	1.5	...		d
191765	WN6	1989 Aug	8	...	...	149.8	1.0	d
192163	WN6	1989 Aug	9	...	...	77.5	1.4	d

[a] From Robert 1991.
[b] ESO 3.6 m telescope with CASPEC echelle spectrograph and CCD; 0.07 Å per pixel.
[c] CFHT 3.6 m telescope with coudé spectrograph and Reticon; 0.10 Å per pixel.
[d] Observatoire du mont Mégantic 1.6 m telescope with grating spectrograph and CCD; 1.325 Å per pixel.

absolute magnitudes are upper limits for the Wolf-Rayet star because the photometry of HD 190918 used by Humphreys (1978) measures the light from all of the stars in the small asterism which contains HD 190918.

3.4. *The Times of Periastron shown by the Orbits of the O and Wolf-Rayet Stars*

The time of periastron passage (Table 3) determined from observations of velocity changes of the Wolf-Rayet star of HD 190918 appears to occur 10.0 days, or 0.089 in phase, earlier than it does in solutions for the O star. This is illustrated by the distribution of points in Figures 2 and 3. The orbital phase of each observed radial velocity is given for the O star and for the Wolf-Rayet star in Table 1. Observations 5 and 6, which for the O star and for the sharp C III emission line occur at phases 0.004 and 0.014 (see Figs. 2 and 4), occur for the Wolf-Rayet star at phases 0.092 and 0.101, see Figure 3.

The O star and the Wolf-Rayet star belong to a gravitationally coupled binary system. Their centers of mass move one-half cycle out of phase with each other. The apparent lead in phase of the radial velocities from the broad He II $\lambda5411$ emission line means that the light center of this line does not follow the motion of the center of mass of the Wolf-Rayet star implied by the O star orbit. The observations indicate that there is a center of light, bright in He II $\lambda5411$, which crosses the line of apsides 10 days in advance of the time when the center of mass of the Wolf-Rayet star reaches this fiducial line in the orbit as determined from observations of the O star. A similar small advance in phase between the He II $\lambda5411$ line of the Wolf-Rayet spectrum and the motion of the O star has been detected for V444 Cygni (Underhill et al. 1988a). The center of light in the broad He II $\lambda5411$ line for both binaries appears to reach the fiducial line for phase before the center of mass of the Wolf-Rayet star does as it moves in antiphase to the O star.

In the case of HD 190918, the velocity curve determined for the Wolf-Rayet star by the best fitting set of orbital elements is somewhat imprecise because of the lack of precision of the Wolf-Rayet velocities. Nevertheless, Figure 3 presents a velocity pattern which complements the motion of the O star quite well except for the shift in systemic velocity and for the shift in time of apparent periastron passage. The values of ω and $T_{\rm peri}$ describe the orientation of the orbit relative to the line of sight. Possibly it would have been more informative to have done a solution with both ω and $T_{\rm peri}$ free to change.

A solution using the Wolf-Rayet radial velocities and adopting only P and e from the O star orbit gives ω(W-R) = 12.0 ± 32.8, $T_{\rm peri}$(W-R = 7408.9 ± 8.9, γ(W-R) = 70.2 ± 4.6, and K(W-R) = 34.5 ± 7.4. In this case ω(W-R) and $T_{\rm peri}$(W-R) are less precisely determined than for the set of elements given in Table 3, but γ and K are effectively the same as in the adopted set of elements. Clearly the line-of-sight changes of motion indicated by the broad He II emission line determine a different orientation for the orbit of the He II $\lambda5411$ light from the Wolf-Rayet star relative to the line of sight than is implied by the motion of the O star. We interpret this to mean that the light center seen by means of He II $\lambda5411$ is not coincident with the mass center of the Wolf-Rayet star.

During the time interval covering the passage through periastron, the Wolf-Rayet star is moving away from the observer. Observations 24 and 25 occur near the moment of maximum positive radial velocity for the Wolf-Rayet star. At this time the O star is still approaching the observer at phase 0.90–0.91 in the O star orbit, so the mass center of the Wolf-Rayet star must be still receding from the observer. At the time of Observations 5 and 6 the O star reaches periastron, however, the Wolf-Rayet center of light still shows a significant positive line-of-sight component of motion. More observations obtained between O-star phases 0.90, through 0.0, to 0.1 are needed to resolve what is going on.

3.5. *The Sharp* C III *Line*

3.5.1. *Motion indicated by the Sharp* C III *Line*

The orbital elements presented in Table 3 determined from the velocity changes of the C III emission line adopt the value of P found for the O star. They describe an orbit like that traced out by the lines formed in the photosphere of the O star except that the plasma emitting the C III emission line has an added line-of-sight component of motion of about -13 km s^{-1} and the eccentricity is larger than for the O star. The eccentricity is not well determined. It is not certain that the C III line tells of the line-of-sight motion of plasma which is moving only as a result of the gravitational forces in the binary system.

A comparison of Figure 2 with Figure 4 shows that it is only for Observations 5, 6, 13, 24, and 25 that a significant difference between the distribution of points about the calculated velocity curve exists. For these five points the average difference $v_{\rm O\,Star} - v_{\rm C\,III}$ is 7.8 ± 2.6 km s^{-1} while for the other 20 points it is 14.8 ± 1.6 km s^{-1}. The latter value agrees reasonably well with the difference $\gamma_{\rm O\,Star} - \gamma_{\rm C\,III} = 13.3$ km s^{-1} corresponding to the sets of orbital elements given in Table 3. Clearly the C III velocities shown by the observations which define the velocity dip around periastron shown in Figure 2 are displaced longward by about 7 km s^{-1} from the displacement shown by the observations obtained outside of the phase range around periastron.

The apparent large change in eccentricity shown by the sharp C III emission line expresses the fact that the plasma forming the C III line shows smaller negative displacements when the system is observed near the time of periastron for the O star, than it does at other phases. The change in eccentricity appears to be a fiction of the algorithm which has been used to analyze the C III radial velocities.

Underhill & Gilroy (1990) and Underhill (1994) have found that the plasma which emits the weak sharp emission lines seen in Of spectra frequently shows small positive or negative displacements relative to the radial velocity indicated by the absorption lines formed in the photosphere of the star. The negative displacements which we have found for the sharp C III emission line in the spectrum of HD 190918 appear to be generally similar to but larger than the small positive or negative displacements of this line seen in Of spectra. These displacements suggest outflow or inflow of the plasma in which the sharp emission lines are formed. The electron temperature of the plasma emitting the sharp C III $\lambda5696$ line may be of the order of 30,000–40,000 K, see Bhatia & Underhill (1988, Fig. 5). There it is shown that C III $\lambda5696$ is particularly strong relative to C IV $\lambda\lambda5801$, 5812 in line-emitting regions containing a velocity gradient when the electron temperature is less than about 40,000 K and $N_e \approx 10^9$–10^{10} cm^{-3}. Often in O9.5 or O9 supergiants the C III $\lambda5696$ line is seen weakly in emission (Underhill 1955). Modern observations of Of, O(f), and O((f)) stars (Underhill 1994, in preparation) show that C III $\lambda5696$ appears in emission in O stars of luminosity classes from V to I.

Narrow sharp emission lines are prominent in the spectrum of the peculiar Of star HD 108. Underhill (1994) has suggested that in that case the sharp emission lines may be formed in a jet almost perpendicular to the light of sight. In the case of HD 190918 the plane of the orbit appears to be inclined at 20°–25° to the plane of the sky (see Table 4 and § 3.6). If the C III line is emitted in a sheath of plasma round the O star, the comparatively narrow width of the C III line, see Figure 1, implies that the outflow velocity of the plasma truly is small; the value -13 km s^{-1} is unlikely to be a projected component of a large terminal outflow velocity associated with a rapidly flowing jet from the O9.5 star. The sharp C III emission line may be formed low in the wind from an O star, if it is formed in the wind at all, cf. Underhill (1984). Possibly in the case of HD 190918 it is formed in moderately hot plasma associated with the stagnation ridge between the colliding winds from the two components of HD 190918, see § 3.7.

3.5.2. *The Colliding Winds Hypothesis*

A possible interpretation of the observations is that the sharp C III emission line is formed in plasma contained in the region where the winds from the two stars collide. During most of the orbit this plasma shows a velocity of about -13 km s^{-1} relative to the O star. When the O star is observed to be near periastron, i.e., when the two stars are least separated and the O star is approaching the observer, the star are almost at right angles to the line of sight because then the angle v is near 0° and $\omega_{O\ Star}$ is near 180°. At this time the impact of the Wolf-Rayet wind on the line-of-sight motion of the plasma forming the C III emission line appears to reduce the component of velocity observed toward the observer of the plasma radiating the C III line. We return to the subject of colliding winds and the sharp C III emission line in the spectrum of HD 190918 in § 3.7.

3.5.3. *The Shape of the* C III *Emission Line*

In order to study possible changes in the shape of the C III emission line with phase in the O-star orbit, we made highly magnified pictures of the C III line profile and stacked them in order of phase. To quantify the profile we measured the central intensity of the emission line and the full extent of its base (FWZI). No significant variation of these quantities with phase in the orbit was found. The average central intensity of the line, determined from 25 spectra, was $3.13 \pm 0.08\%$ of the continuum height, while the average FWZI was 10.13 ± 0.15 Å. No changes in excess of the uncertainty of measurement were found in the central intensity and FWZI. However, the shape of the line profile appeared to change slowly throughout the observing interval 1986–1992. The changes do not appear to be tightly related to the phase in the radial-velocity orbit. They are discussed in § 3.7.4 as part of the colliding-winds hypothesis.

3.6. *Properties of the Orbit of* HD 190918

3.6.1. *The Masses of the Stars of* HD 190918 *and the Dimensions of the Orbits*

The masses of the components of HD 190918 and the semi-major axes of the elliptical orbits implied by the adopted sets of orbital elements (Table 3) are given in Table 4 for four values of i, the inclination of the plane of the orbit to the plane of the sky. Since the spectral type of the O star is O9.5, the cases $i = 25°$ or $i = 20°$ are possible solutions. When $i = 25°$ the mass of the O star is typical for a late O-type main sequence star; when $i = 20°$, the mass suggests an O9.5 supergiant star.

At types B1 to O9 the luminosity class is determined by absorption line ratios involving (Si IV λλ4089+4116)/He I λ4121, He II λ4541/He I λ4387, Si III λ4552/He I λ4387, and He II λ4686/He I λ4713 (see, for instance, Table 1-1 of Divan & Prévot-Burnichon 1988). However in the case of HD 190918 these line ratios cannot be used because the presence of the strong emission lines due to He II and He I distorts the background against which the O-type absorption lines are seen. Therefore one cannot tell surely the luminosity class of the O star by inspection of blue-violet spectrograms. We shall have to use other properties of the system HD 190918 to infer the luminosity class of the O star.

In what follows we shall concentrate our attention on cases when $i = 20°$ or 25°. If i is as large as 30°, then the mass of the absorption line star is small for an O star while if i is 15°, the mass is larger than what is known from spectroscopic binaries to be true for late O-type stars. With i in the range 20°–25°, the mass of the Wolf-Rayet star ranges from 5.4 to 10.1 $M_\odot$. Such values are modest for Wolf-Rayet stars. The observed ratio $K_{O\ Star}/K_{W\text{-}R\ Star}$ implies that $M_{O\ Star}/M_{W\text{-}R\ Star} = 2.0$.

Robert et al. (1989) have presented a few polarization observations of HD 190918. These observations are compatible with the binary character of the star. However, they are poorly distributed in time for determining a value of i. The polarization observations are compatible with i in the range suggested by the radial velocity results, although Robert et al. prefer the complementary inclination $180 - i$, where i is in the range explored in Table 4. Because Robert et al. use an entrance aperture of 10 arcsec for their photometric observations and because HD 190918 is the central star of a small group of stars, the polarization attributed to HD 190918 by Robert et al. is diluted by light (presumably unpolarized) from the companion stars. These are probably of type B because they are 2–3 magnitudes fainter than the spectroscopic pair HD 190918.

The orbits of the components of HD 190918 are quite large relative to the typical sizes of hydrogen-burning stars of the masses of the stars in HD 190918, see Table 4. Typically a 10 $M_\odot$ main-sequence star has a radius of about 12 $R_\odot$, while the radius of an O9.5 Ia star may be 35 $R_\odot$ (Divan & Prévot-Burnichon 1988, p. 59).

It is interesting to compare the orbital elements for HD 190918 with those (Niemela & Sahade 1980) for HD 68723 γ^2 Velorum. In the case of γ^2 Velorum the companion is classified as O9 I, the period is rather long (78.5 day compared with 112.4 day for HD 190918), the eccentricity is near 0.40 for both systems, and the orbits are large relative to the sizes of the component stars. Because no eclipse is known for γ^2 Velorum and the minimum mass of the companion O star is large, it seems likely that $i \approx 70°$ for γ^2 Velorum. Aside from this difference and from the fact that the spectral type of the Wolf-Rayet star in γ^2 Velorum is WC8, the system HD 190918 is similar to that of γ^2 Velorum. In neither case can we be sure from looking at the spectrum that the companion is truly a supergiant.

3.6.2. *The Swath Cut by the O Star through the Wind of the Wolf-Rayet Star of* HD 190918

If the O star of HD 190918 is a main-sequence star, i may be 25°. Then the separation of the centers of the stars is 1.46×10^{13} cm at periastron and 1.99×10^{13} cm at apastron. If the companion is a supergiant, $i = 20°$, the separation of the centers of the stars is 1.81×10^{13} cm at periastron and

2.46×10^{13} at apastron. In the first case the radius of the star may be 12 $R_\odot$ (8.35×10^{11} cm) while in the second case the radius may be 35 $R_\odot$ (2.44×10^{12} cm).

Two models may be considered for the line-emitting region (LER) of the Wolf-Rayet star. Model I, following Bhatia & Underhill (1988), is a ringlike disk with an inner radius of the order of a few $\times 10^{13}$ cm and an outer radius of, perhaps, 10^{14} cm. The ring is attached to the Wolf-Rayet star by a few magnetically supported filaments, see the Appendix. In this case the orbital motion of the two stars takes place inside the ringlike LER. The LER is dragged by the Wolf-Rayet star as it moves around the O star.

One may think of the Wolf-Rayet star as stationary. The O star then moves around the Wolf-Rayet star in an ellipse with $e = 0.39$ and the separations of the centers of the stars at periastron and apastron will be as given above. In the case that $i = 25°$, the O star is a main-sequence star, its spectral type is O9.5 V. The companion cuts a swath through the central hole of the Wolf-Rayet LER. This swath has diameter of $2R_{\rm O\,star} = 1.67 \times 10^{12}$ cm. As the O star moves on its path it will encounter the few filaments which attach the ringlike disk to the body of the Wolf-Rayet star, but it will not impinge on the main body of the LER. In the case that $i = 20°$, the O star is a supergiant, type O9.5 Ia. Then the swath has a diameter of 4.88×10^{12} cm and it will be positioned such that the periastron separation of centers is 1.81×10^{13} cm and the apastron separation is 2.46×10^{13} cm. The star as it moves on its path will encounter a few filaments, but it need not encounter the ringlike LER if the inner radius of the LER is 3×10^{13} cm or larger. In the case of Model I the central body of the Wolf-Rayet star emits a low-density wind which may correspond to a rate of mass loss of $\leq 5 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$. This wind radiates f-f bremsstrahlung in both the infrared and radio ranges. The ringlike LER also radiates a wind and this disk-driven wind generates a radio flux, see Underhill (1986) for a description of what may occur.

An alternative model, Model II, for the LER of a Wolf-Rayet star is that the LER consists of a dense spherical wind which has the density pattern which follows from adopting a rate of mass loss of the order of $5 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ for the Wolf-Rayet star and a velocity law which describes how the outflow velocity develops from a value near the speed of sound at the continuum-forming layers of the Wolf-Rayet star to $v_\infty \approx 1600$ km s^{-1} when r is large. In the case that $i = 25°$, the O star cuts a swath of diameter 1.67×10^{12} cm through the wind and the swath moves from a separation of centers of the stars of 1.46×10^{13} cm at periastron to 1.99×10^{13} cm at apastron. In the case that $i = 20°$, the O star cuts a swath of diameter 4.88×10^{12} cm through the wind, moving from a separation of centers of 1.81×10^{13} cm at periastron to 2.46×10^{13} cm at apastron. With Model II, the O star is buried in the dense wind of the Wolf-Rayet star at all times. Consequently one might expect to see colliding-plasma effects at all times as the O star travels through the wind, if the wind is not too optically thick.

With Model I, the wind from the central star is not dense, by hypothesis. (The known comparatively large radio fluxes from the Wolf-Rayet stars are generated chiefly by disk-driven winds in the case of Model I.) Consequently colliding plasma effects should be minimal in the case of Model I. They may be expected to occur in the central hole of the LER. With both Models I and II an X-ray flux may be generated as the wind from the Wolf-Rayet star collides with that from the O star. If the companion is a main-sequence star, the rate of mass loss from the O star may be of the order of $10^{-8}\ M_\odot\ {\rm yr}^{-1}$ while if it is a supergiant the rate of mass loss from the O star may be of the order of $10^{-6}\ M_\odot\ {\rm yr}^{-1}$. The possible X-ray luminosity is described in § 3.7.

3.6.3. *Comparison with the Systems V444 Cygni and γ^2 Velorum*

The orbit of V444 Cygni is small and circular. The period is 4.212424 days and from the orbital elements of Underhill et al. (1988a) the separation of the centers of the stars is 2.66×10^{12} cm. The spectral types are O6 and WN5. If one uses $i = 78°$ as indicated by solutions of the light curve, $M_{\rm O\,Star} = 37.5\ M_\odot$, and $M_{\rm W\text{-}R\,Star} = 11.3\ M_\odot$. The radius of the O star may be 15 $R_\odot$ (1.04×10^{12} cm) (Divan & Prévot-Burnichon 1988), while that of the Wolf-Rayet star may be of the order of 10 $R_\odot$ (0.70×10^{12} cm). The stars move nearly in contact, the distance between the inner edges of the two stars being of the order of 0.9×10^{12} cm. Because the stars are nearly in contact, it is not surprising that changes in the spectrum and light are seen throughout the orbit of V444 Cygni, see, for instance, Underhill & Fahey (1987) and Underhill et al. (1988b).

It was noted above that the system HD 68723 γ^2 Velorum is similar to that of HD 190918 in some respects. If it be assumed that the inclination of the γ^2 Velorum system is 70°, the separation of the centers of the two stars is 1.79×10^{13} cm at periastron and 2.47×10^{13} cm at apastron. A smaller inclination makes the separations even larger. Even if the radius of the O star is as large as 35 $R_\odot$ (2.44×10^{12} cm) while that of the Wolf-Rayet star is of the order of 10 $R_\odot$ (0.7×10^{12} cm), the stars are not in close contact at any time in their orbit, just as is the case for HD 190918.

While the present paper was being completed, St. Louis, Willis, & Stevens (1993) published a paper describing the phase-dependent ultraviolet spectral changes of γ^2 Velorum and compared these changes to what is known for V444 Cygni. These changes are significant and they are suggestive of what may be true for HD 190918.

St. Louis et al. give an interpretation of the ultraviolet spectrum of γ^2 Velorum in terms of the collision of the spherical winds from the WC8 star ($\dot{M}_{\rm WR} = 8.8 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$) and the O9 I star ($\dot{M}_{\rm O} = 1.3 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$). They adopt orbital elements for γ^2 Velorum which are similar to those we have used. St. Louis et al. give a qualitative interpretation of what is seen in terms of scattering of the O star light by the wind of the Wolf-Rayet star and the effects of colliding winds. They conclude that the detailed phase-dependent nature of the line-profile changes is consistent in broad terms with the model which they describe.

Another possible model, that of Bhatia & Underhill (1988), may be used for both HD 190918 and γ^2 Velorum. In it the O-type companion moves around the Wolf-Rayet star in the hole between the surface of the Wolf-Rayet star and the LER. The LER is in the form of a large, thin, ringlike disk some 3×10^{13}–10^{14} cm from the center of the Wolf-Rayet star. In this model, the Wolf-Rayet star emits a moderate density, spherical wind, $\dot{M}_{\rm WR} \approx 5 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$, while the companion has properties similar to what St. Louis et al. adopt. Can a model such as that described by Bhatia & Underhill (1988) generate phase-dependent changes in the ultraviolet spectrum such as St. Louis et al. observe?

It seems possible that this is so. One should recall that with such a model the line-emitting ringlike disk will generate about the same emission-line spectrum no matter at what phase angle it is observed, while the light which comes from the photosphere of each star will reach the observer modified by extinction in lines and continuum depending on how much of the line of sight passes through the plasma of the disk and through the winds from the two stars at each orientation of the two stars. In our discussion of the systems of HD 190918 and γ^2 Velorum the system of phases is defined such that phase 0.0 corresponds to the time of periastron. This is different from the convention used by St. Louis et al. (1993). Their phase 0.0 corresponds to phase 0.61 on our system, that is a little past apastron, and their phase 0.5 corresponds to phase 0.11 on our system, or a little past periastron. They use JD 2,445,768.96 as the moment when phase equals 0.0 while we use JD 2,432,846.8; we both use $P = 78.5002$ days.

In order to draw a precise picture, let us think of a system with the core of the Wolf-Rayet star at the center of a large, thin, ringlike disk which lies in the orbital plane. In the case of γ^2 Velorum this plane has an inclination of about 70° to the plane of the sky. We postulate that the disk fills a ring which has a flare of $\pm 10°$ with respect to the plane of the orbit. The inner radius of the disk may be 3×10^{13} cm while the outer radius may be of the order of 10^{14} cm. In the disk, the electron density is of the order of 10^{10}–10^{11} cm^{-3}, the electron temperature is a little less than 10^5 K, and the disk is transparent in continuum frequencies, see Bhatia & Underhill (1988).

With this model for γ^2 Velorum, the O star at periastron lies on the plane of the orbit near the inner edge of the disk on the front side of the orbit. At apastron, the O star lies on the plane of the orbit on the far side of the orbital plane and inside the inner edge of the line-emitting disk. According to St.Louis et al. (1993), the diameter of the O star is of the order of 42 $R_\odot$ (2.9×10^{12} cm), while that of the Wolf-Rayet star is 22 $R_\odot$, thus 1.5×10^{12} cm. The extent perpendicular to the plane of the orbit of the disk which we postulate is of the order of 5.2×10^{12} cm at the inner edge of the disk.

At periastron the light of the O star will pass through the outer part of the wind of the Wolf-Rayet star and it may pass through the lower half of the disk. It may be modified by scattering in the resonance lines which are formed in the Wolf-Rayet wind and in the disk. At apastron, see Figure 9 of St. Louis et al. (1993), the direct line of sight to the O star will pass below the flare of the near side of the disk; it will pass through most of the wind of the Wolf-Rayet star, both on the back side and on the nearside, as well as through any trailing extensions or filaments hanging from the near side of the disk which may cross the line of sight. (A possible description of the filamentary part of the disk and the effects of this structure on the ultraviolet spectrum has been given in the case of V444 Cygni by Underhill & Fahey 1987.) At apastron one expects to see significant modifications to the ultraviolet light from the O star as a result of scattering at the frequencies of the resonance lines of ions in the Wolf-Rayet wind and from any continuous absorption due to continuous opacity (mostly electron scattering) there. Because there is no sure information pointing to an "eclipse" of the O star in continuum wavelengths, see the discussion by St. Louis et al. (1993), the wind of the Wolf-Rayet star should not be dense at any place where the light from the O star traverses it. This constraint is less certain to be true when $\dot{M}_{\rm WR} = 8.8 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ as St. Louis et al. (1993) suggest than in our model where $\dot{M}_{\rm WR} \approx 5 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$.

Our suggested model for γ^2 Velorum can qualitatively explain the observations reported by St. Louis et al. (1993) because it allows for a long path through the wind of the Wolf-Rayet star for the light of the O star near apastron and a short path in the case of periastron. Only in the case of phases near periastron may the light from the O star pass through the ringlike disk. The disk, by hypothesis, is transparent in continuum frequencies. Describing our model by means of a numerical model is outside the scope of the present paper.

We would not expect the system HD 190918 to show phase-dependent changes of its ultraviolet spectrum as conspicuous as those of γ^2 Velorum because the inclination of HD 190918 is of the order of only 20°–25°. Consequently the path length of the light from the O star through the Wolf-Rayet wind does not change greatly with phase in the orbit. In addition, unless the disk has a large flare (of the order of $\pm 60°$), the line of sight from the O star will not intersect a somewhat extended rim of the Wolf-Rayet LER at any phase.

Careful documentation of the phase-dependent changes in the resonance lines of the spectra of WR + O binaries can yield new information which may be important for deciding between the possible models for Wolf-Rayet stars. An attack on this problem using ground-based observing equipment may be made by observing the phase-dependent changes of the He I λ10830 line because this line, is, in essence, the resonance line of the triplet species of He I.

If the ultraviolet lines of Fe IV, Fe V, and Fe VI, almost all of which have metastable lower levels, generate phase-dependent absorption troughs in the ultraviolet spectrum of γ^2 Velorum as St. Louis et al. (1993) argue, then one would expect a similar phase-dependent trough to be generated for He I λ10830. The He I λ10830 line may act as a surrogate in some respects for the ultraviolet lines from ground and metastable levels.

3.7. HD 190918 *as an X-ray Source*

Because both stars of HD 190918 have winds, one may expect X-rays to be generated in the hot plasma formed in the region where the winds collide. The problem of colliding winds when one star is a Wolf-Rayet star has been modeled numerically by Stevens, Blondin, & Pollock (1992). It has been treated analytically by Usov (1992). In this section we shall compare what may be observed for HD 190918 and what has been observed for V444 Cygni and γ^2 Velorum with what may be estimated.

3.7.1. *Observed X-ray Fluxes*

The X-ray luminosities of Wolf-Rayet stars resulting from observations with the *Einstein* satellite in a band from 0.2–4 keV have been compiled by Pollock (1987). Unfortunately the *Einstein* satellite did not observe the field of HD 190918 (F. R. Harnden 1993, private communication), but it did observe V444 Cygni and γ^2 Velorum. The inferred X-ray luminosities in the 0.2–4 keV band (Pollock 1987) are $L_{\rm X}$(V444 Cyg) = $7.7 \pm 1.3 \times 10^{32}$ ergs s^{-1} and $L_{\rm X}(\gamma^2$ Vel) = $1.1 \pm 0.2 \times 10^{32}$ ergs s^{-1}. These two stars have count rates per 100 s of 1.5 and 6.0, respectively. It is interesting that although γ^2 Velorum is at less than one-third the distance of V444 Cygni, the X-ray count rate of V444 Cygni, which is a star behind considerable dust, is as large as one-quarter that from γ^2 Velorum. One would expect distance and interstellar extinction to generate a reduction factor greater than 9.

3.7.2. *Theoretical Studies of Colliding Winds*

Stevens et al. (1992) explored detailed hydrodynamic models for V444 Cygni and for γ^2 Velorum. They predicted $L_{\rm X} = 3.2 \times 10^{34}$ ergs s^{-1} in the 0.2–4 keV band for V444 Cygni and concluded that the observed X-rays might rather come from shocks intrinsic to the winds of both stars than from colliding winds with the properties of their model. In the case of V444 Cygni, the stars are so close together that it is critical what one assumes for the velocities of the winds as they collide at the stagnation ridge. The opacity to X-rays of the relatively dense plasma of the stagnation ridge and the cooling which takes place in this plasma are important factors affecting the flux of X-rays which escapes.

Stevens et al. (1992) discuss also the case of γ^2 Velorum in some detail. They conclude that this system will produce a very complex but rewarding example of a colliding-wind binary. Because of the general similarity between the orbits of γ^2 Velorum and HD 190918, the latter star should also prove to be a rewarding object to observe in X-rays throughout its long period.

Usov (1992) has developed analytical expressions by means of which one may obtain a first estimate of the X-ray luminosity which may be generated in the hot plasma formed in the stagnation ridge where the winds meet each other. Equations for two cases are given. V. V. Usov (1993, private communication) states that his equation (81) evaluates the expected X-ray luminosity when the parameter r_{OB}/R_{OB} is less than 1.0, and that the sum of the results from his equations (89) and (95) is to be used when r_{OB}/R_{OB} is greater than 1.0. When this ratio is close to or less than 1.0, the stagnation ridge is effectively on the surface of the O star. Then one may expect much extinction of the X-rays by overlying plasma. Here r_{OB} is the distance from the center of the O star to the stagnation ridge and R_{OB} is the radius of the OB star. The rate of cooling of the colliding winds is an important parameter, see also the discussion by Stevens et al. (1992).

3.7.3. *Predicted X-ray Luminosities from Wolf-Rayet Binaries*

If one ignores the cooling of the colliding plasma, Usov's equations will yield upper limits to the luminosity in X-rays to be expected. We have estimated these upper limits for HD 190918 and γ^2 Velorum using Usov's equations (81), (89), and (95) and making rough estimates of the cooling and extinction to be expected (V. V. Usov 1993, private communication). We used the separation of the centers of the stars derived from the binary orbits together with estimates of the radii of the stars, the rates of mass loss, and terminal velocities of the winds. We assume $v^{\infty}_{\text{W-R}} = v^{\infty}_{\text{O star}} = 1600$ km s^{-1}. Usov's equations (2) and (3) can be used with these adopted data to find the implied values of the ratio r_{OB}/R_{OB}. In what follows we discuss the significance of these predictions. Because the stars are too close together in the system V444 Cygni for Usov's equations to give a reliable estimate of the expected X-ray luminosity, we investigate this system no further.

The estimated X-ray luminosities for HD 190918, using Usov's equations, are listed in Table 7 for four cases. Three conclusions are possible.

1. If the observed X-ray luminosity is of the order of 10^{31} ergs s^{-1} or smaller, Cases II and III are possible. In Case II the companion is a supergiant, $\dot{M}_{\text{W-R}}$ is of the order of 5×10^{-5} $M_\odot$ yr^{-1}, and the extinction throughout the orbit is an important factor. In Case III the companion is a main-sequence star and $\dot{M}_{\text{W-R}}$ is of the order of 5×10^{-6} $M_\odot$ yr^{-1}; extinction is an important factor.

2. If the observed X-ray luminosity is of the order of 10^{32} ergs s^{-1}, Cases I and II are possible. In Case I the companion is a main sequence star and $\dot{M}_{\text{W-R}}$ is of the order of 5×10^{-5} $M_\odot$ yr^{-1}. Case II is described under Conclusion 1.

3. If the observed X-ray luminosity is of the order of 10^{33} ergs s^{-1}, Case IV is possible; the companion is a supergiant and $\dot{M}_{\text{W-R}}$ is of the order of 5×10^{-6} $M_\odot$ yr^{-1}.

TABLE 7

PREDICTED UPPER LIMITS TO X-RAY FLUXES FROM HD 190918

Case	$\dot{M}_{\text{W-R}}$ ($M_\odot$ yr^{-1})	$\dot{M}_{OB}$ ($M_\odot$ yr^{-1})	r_{OB}/R_{OB} Range[a]	Upper Limit to L_X (ergs s^{-1})	Notes
I	5×10^{-5}	10^{-8}	0.24–0.33	A few $\times 10^{32}$	
II	5×10^{-5}	10^{-6}	0.92–1.25	About 10^{34}	b
III	5×10^{-6}	10^{-8}	0.75–1.02	A few $\times 10^{31}$	c
IV	5×10^{-6}	10^{-6}	2.29–3.12	A few $\times 10^{33}$	

[a] The quantity r_{OB} is the distance from the center of the OB star to the shocked region; R_{OB} is the radius of the OB star. When r_{OB}/R_{OB} is in the range $1 \pm \delta$ and $\delta \approx 0.2$–0.3, the dense plasma of the shocked region may extinguish most of the X-rays. The tabulated range gives the value of r_{OB}/R_{OB} from periastron to apastron. Values less than 1.0 indicate that the shock is on the surface of the O star.

[b] During most of the orbital period extinction in Case II will reduce L_X from its predicted value. At apastron, the expected L_X may be about 10^{33} ergs s^{-1}.

[c] During most of the orbital period extinction in Case III will reduce L_X from its predicted value; L_X may be near the tabulated limit at periastron.

Thus knowledge of the X-ray luminosity from HD 190918 obtained at phases around the orbit may point to the luminosity class of the companion star and to the rate of mass loss from the Wolf-Rayet star.

In order to estimate the X-ray luminosity from γ^2 Velorum using Usov's equations, we make use of the orbital elements of Niemela & Sahade (1980) and assume dimensions, terminal velocities, and rates of mass loss from the two stars as for HD 190918. When one adopts an inclination of 70° for the orbital plane of γ^2 Velorum and postulates that the companion is a supergiant star as for Cases II and IV of HD 190918, then if $\dot{M}_{\text{W-R}} = 5 \times 10^{-5}$ $M_\odot$ yr^{-1}, the upper limit to the X-ray luminosity is about 1.2×10^{36} ergs s^{-1} while if $\dot{M}_{\text{W-R}} = 5 \times 10^{-6}$ $M_\odot$ yr^{-1}, this upper limit may be about 3.6×10^{34} ergs s^{-1}. Both values are larger than the observed value (Pollock 1987) of 1.1×10^{32} ergs s^{-1}. If the companion is a supergiant, it is important to estimate the extinction and cooling accurately at phases around the orbit. If the companion is a main-sequence star with $\dot{M}_{OB} = 10^{-8}$ $M_\odot$ yr^{-1}, then the predicted upper limits are reduced by a factor 10^{-3}. Such values are of the order of the observed L_X for γ^2 Velorum.

These estimated L_X-values suggest that the companion to γ^2 Velorum may be a main-sequence star. We recall that we noted in the case of HD 190918 that visual inspection of spectrograms does not establish the luminosity class of the O star in a massive binary in a secure manner. The mass for the O star which results from using the orbital elements from Niemela & Sahade (1980) with $i = 70°$ is 38.6 $M_\odot$. This is large for a main-sequence O9 star. Some uncertainty exists about the correct values of the mass ratio and semiamplitudes of the stars in the system γ^2 Velorum, see Niemela & Sahade (1980), Pike, Stickland, & Willis (1983), and Moffat et al. (1986).

Stevens et al. (1992) give no predicted L_X for γ^2 Velorum; however, they emphasize that this system may be expected to show an X-ray flux which varies throughout the orbital period as a result of cooling of the plasma and the extinction of X-rays.

It may be possible to decide whether or not the rate of mass loss from the Wolf-Rayet stars of HD 190918 and γ^2 Velorum is as small as 5×10^{-6} $M_\odot$ yr^{-1} from the X-ray fluxes observed around the orbits. A value of $\dot{M}_{\text{W-R}}$ of the above size is suggested by the rate of period change of V444 Cygni (Underhill, Grieve, & Louth 1990c).

3.7.4. *Changes in the Profile of the* C III *Emission Line*

Stevens et al. (1992) have shown by means of hydrodynamic models that when the winds from two massive stars collide, an extensive region of inhomogeneous plasma is created, see their Figures 6–8. Strongly cooling winds produce extensive tongues of chaotic plasma perpendicular to the line joining the centers of the stars.

Lines such as C III $\lambda 5696$ may be emitted by such plasma. Certainly this line is not formed in the very high-temperature plasma ($T \geq 10^6$ K) in which the X-rays are formed. Because it is observed that the C III $\lambda 5696$ emission line is seen in the spectra of late O type supergiants (Underhill 1955), the weak, sharp C III line which is observed may possibly be intrinsic to the atmosphere of the O type star of HD 190918. Extensive tongues of somewhat cooled plasma such as the calculations of Stevens et al. (1992) suggest are present in a colliding-winds binary appear to offer a possible place of formation for the sharp C III emission line which we have observed in the spectrum of HD 190918. According to our radial-velocity measurements, the plasma radiating the C III $\lambda 5696$ line moves more or less with the center of mass of the O star except that at phases outside the interval of periastron passage this plasma shows a line-of-sight component of velocity relative to the O star of about -14 km s^{-1} while at phases close to periastron this velocity displacement may be more positive by about 7–8 km s^{-1}. Because the C III line is shifted relative to the line-of-sight velocity of the O star, we infer that in HD 190918 the O star may be shrouded in a sheath of chaotic, moderately hot plasma which contains the stagnation ridge where the winds collide.

Our findings (§ 3.5.3) about the changing shapes of the moderately wide (FWZI = 10.1 ± 0.15 Å or 533 km s^{-1}), weak (central intensity of 1.031 ± 0.001) C III emission line are presented in Table 8. We suggest that the observed changes in line profile are a result of hydrodynamic flows such as those modeled by Stevens et al. (1992). The observed pattern of changes does not correlate well with phase in the O star orbit, although a weak correlation with phase exists in the sense that the spectrograms obtained between phases 0.170 and 0.392 are almost the inverse of those obtained between phases 0.655 and 0.693. In the first group one weak peak appears shortward of the main peak while in the second group two blended peaks are seen longward of the main peak. At other phases the profile of the C III line shows a single peak with a FWHM of about 5 Å (263 km s^{-1}) and moderately extensive wings.

Our observations of the C III $\lambda 5696$ emission line confirm the predictions of Stevens et al. (1992) that extensive tongues of chaotic, cooling plasma are formed when the winds of massive stars collide in addition to bodies of very hot plasma which may radiate X-rays. The cool, chaotic tongues of plasma are more or less perpendicular to the line joining the centers of the two stars. The calculations of Stevens et al. and our observations suggest that changes in the spatial distribution and physical state of the cooling plasma occur slowly for systems of the size of HD 190918.

4. SUMMARY

We have presented new radial-velocity observations for the stars of the WN4.5+O9.5 Ia binary system HD 190918 from 25 yellow-green spectrograms and solved for a definitive set of orbital elements to represent the changes in line-of-sight motion of the stars. The results are given in Table 3 together with a solution representing the observed radial-velocity changes of the weak sharp C III $\lambda 5696$ emission line which appears on each spectrogram.

The plasma generating the C III emission line moves more or less with the O star. In § 3.7 we discuss HD 190918 as a possible X-ray source and we argue that the sharp C III emission line is formed in a hydrodynamic flow of cooling plasma associated with the stagnation ridge formed by the collision of winds from the Wolf-Rayet and the O star.

The period of the system is 112.4 ± 0.2 days and the eccentricity is 0.39 ± 0.07. The semi-amplitude of the O star motion is 16.9 ± 2.1 km s^{-1} while tht of the Wolf-Rayet star is 34.4 ± 7.4 km s^{-1}. We find that if $i = 25°$, $M_{\rm O\,star} = 10.5\ M_\odot$ while if $i = 20°$, $M_{\rm O\,star} = 20.6\ M_\odot$. The corresponding masses for the Wolf-Rayet star are 5.4 $M_\odot$ and 10.1 $M_\odot$, respectively. In the first case the O star may be a main-sequence star, in the second a supergiant. The orbit of HD 190918 is similar in size to that of HD 68723 γ^2 Velorum.

We note in § 3.4 that the light center for HD 190918 seen by means of the Wolf-Rayet line He II $\lambda 5411$ appears to pass through periastron about 10 days before the center of mass of the Wolf-Rayet star, when moving in antiphase to the O star, should do so. A similar small discrepancy in phase has been noted for V444 Cygni (Underhill et al. 1988a). Discrepancies of this sort suggest that the line-emitting regions of Wolf-Rayet stars in binary systems are not spherically symmetric about the center of mass of the star. When one has several lines by which to track the line-of-sight motion of the Wolf-Rayet star, as in the case of CQ Cephei (Underhill et al. 1990b), one finds each line gives a different semiamplitude and time of periastron passage. This has the result that it is by no means sure that the strongest unblended emission lines truly track the motion of the center of mass of the Wolf-Rayet star.

It is impossible to tell the luminosity class of the O star of HD 190918 securely from inspecting spectrograms of the blended spectra because the relative intensities of the absorption lines usually used as luminosity criteria at types B1–O9

TABLE 8

THE SHAPE OF THE C III EMISSION LINE AS A FUNCTION OF TIME

Year	Number of Observations	Shape of Profile
1986	1	Smooth hump with structured longward wing.
1987	5	Smooth hump with symmetric wings.
1988	7	Smooth hump with symmetric wings.
1990	5	Asymmetric main hump plus a weak shortward hump.
1991	5	Two peaks longward of the main hump; shows slow change.
1992	2	Sharp hump with smooth wings to either side.

are disturbed by blends with the broad emission lines of the Wolf-Rayet spectrum. We argue in § 3.7 that an observation of the X-ray flux from HD 190918 may help us choose between the possibilities and decide about the rate of mass loss from the Wolf-Rayet star.

The systemic velocity of the O star is -20.9 ± 0.7 km s^{-1} while that of the Wolf-Rayet star is 70.2 ± 4.6 km s^{-1}. The systemic line-of-sight motion of the O star is appropriate for the expected motion of a Population I star which is a member of Cyg OB3. This means, as has long been known for HD 190918 and other O + WR binaries, that the He II lines are intrinsically displaced longward by approximately 100 km s^{-1}. In § 3.3.1 we review evidence that this systematic shift of the He II lines is intrinsic to the spectra of all Wolf-Rayet stars and we note that lines from the ions of C and N are seen to be intrinsically displaced shortward by about 50 km s^{-1}. Following Underhill & Yang (1991) we suggest that the longward displacement of the He lines results from infall from remnant material from the star formation process. The front part of the large, ringlike disk which according to the model of Bhatia & Underhill (1988) forms a main part of the line-emitting region of a Wolf-Rayet star contributes to this infall while the displacements of lines from the C and N ions are generated by motions of hot plasma in filaments attached to the photosphere of the Wolf-Rayet star and seen projected against the face of the star. The ever changing filaments link the large, ringlike disk to the body of the Wolf-Rayet star, see the Appendix.

We note in § 3.6.2 that the O star cuts a swath through the wind of the Wolf-Rayet star. What spectroscopic effects might be generated depends on whether one adopts a model for the LER of the Wolf-Rayet star as recommended by Bhatia & Underhill (1988) or whether one assumes that the LER is a dense spherical wind. In the case of the first type of model, the O star in its orbital motion moves in the large central hole of the disk, the hole being, perhaps, 3×10^{13} cm in radius. The O star impinges only on the few ever changing filaments which link the ringlike disk to the central star. The core of the Wolf-Rayet star fills the hole and surrounding space with a low-density wind, $\dot{M}_{\text{W-R}} \leq 5 \times 10^{-6}\ M_{\odot}$ yr^{-1}. In § 3.6.3 we noted that this type of model is useful for interpreting spectral changes such as those described by St. Louis et al. (1993) for γ^2 Velorum.

We note that if the LER of the Wolf-Rayet star is formed by a dense spherical wind with $\dot{M}_{\text{W-R}}$ of the order of or greater than $5 \times 10^{-5}\ M_{\odot}$ yr^{-1}, the O star will be buried in the wind and one might expect to see spectroscopic features generated by the collision of the body of the O star and its wind with the wind from the Wolf-Rayet star if the wind from the Wolf-Rayet star is not too optically thick. We noted in § 3.7 that the only effect of colliding winds which we see optically in the case of HD 190918 is a fairly sharp, weak C III emission line which more or less tracks the line-of-sight motion of the O star and which changes its shape slowly. In the case of the model proposed by Bhatia & Underhill (1988), the rate of mass loss from the central star is an order of magnitude smaller than in the case of the traditional dense spherical wind model. Consequently one is not surprised at a lack of conspicuous colliding winds effects.

Further spectroscopic observations (ultraviolet, visible range, and infrared) of HD 190918, particularly near periastron, and X-ray observations carried out throughout the orbital period should help to resolve some of the issues raised here. Extensive polarization observations made throughout the orbit should be useful for confirming our inferred inclination.

We are pleased to acknowledge the assistance of Nadine Dinshaw and E. J. Kennelly with making some of the observations. We are grateful to the Dominion Astrophysical Observatory for a generous allotment of observing time over the years and to Graham Hill for allowing us to use his radial-velocity orbit program RVORBIT. The freely given advice on the use of this program provided by D. Holmgren has proved to be an important factor in the success we have achieved toward reaching a definitive orbital solution for the difficult system HD 190918. We are particularly grateful to V. V. Usov for much guidance with estimating the X-ray luminosities of binary systems containing a Wolf-Rayet star. This research has been supported since 1986 by grants from the Natural Sciences and Engineering Research Council of Canada to A. B. U.

APPENDIX

PROPERTIES OF A DISKLIKE LINE-EMITTING REGION OF A WOLF-RAYET STAR

Bhatia & Underhill (1988) inferred that the line-emitting region (LER) of a Wolf-Rayet star very likely has the form of a thin ringlike disk. This shape is necessary in order that the LER should have a large volume (10^{43}–10^{44} cm^3) and yet be optically thin in electron scattering opacity no matter in what direction a line of sight in continuum radiation traverses it. The ringlike disk described by Bhatia & Underhill (1988) and by Underhill & Yang (1991) is attached to the central core of the Wolf-Rayet star by a few filaments supported by magnetic-field lines of force. This disk is a simplified version of the schematic set of large plumes moving in the plane of the orbit which are described by Underhill & Fahey (1987) as forming the LER of the close WR + O binary system V444 Cygni. The set of plumes which, in effect, form a disk, moves with the core of the Wolf-Rayet star as the star moves in its orbit about the O star. The O-type companion may be described as moving around the core of the Wolf-Rayet star in a gap, which is crossed by a few filaments between the surface of the core and the inner edge of the ringlike disk.

Bhatia & Underhill (1988) and Underhill & Yang (1991) suggest that the LER of a Wolf-Rayet star may have the following dimensions: (1) the core of the Wolf-Rayet star has a radius of the order of that appropriate for a hydrogen-burning star of the mass of the Wolf-Rayet star, say, 10–12 $R_{\odot}$; (2) the inner radius of the LER may be of the order of 10^{13} cm; (3) the outer radius may be of the order of 10^{14} cm; (4) the ions and electrons in the ringlike disk are confined to magnetic loops by a weak magnetic field, one of less than about 100 gauss; (5) the electron density (N_e) in the ringlike disk is of the order of 10^{10} cm^{-3} while the electron temperature (T_e) is of the order of 10^5 K; (6) the thickness of the disk perpendicular to the plane of the orbit (and, presumably, to the equatorial plane of the core of the Wolf-Rayet star) may be of the order of 20 $R_{\odot}$ or 1.4×10^{11} cm.

Underhill (1991) has summarized how the emission-line spectrum of a Wolf-Rayet star is generated in the LER. At the distances from the central core of the star envisaged for the plasma of the disk and at the adopted T_e and N_e, electron collision processes for exciting and de-exciting the ions in the disk tend to dominate radiative processes. Bhatia & Underhill (1986, 1988, 1990) have described the physical processes which form the observed spectrum. They conclude that the composition of the central core of the Wolf-Rayet star and of the disk is typical of stars of Population I, i.e., essentially solar. The effective temperature of the core of the Wolf-Rayet star is typical for a hydrogen-burning star having a mass of 10–15 $M_\odot$ i.e., about 25,000–30,000 K.

Underhill (1986) has suggested that a Wolf-Rayet star is a young star only now arriving on the ZAMS. The remnant of the molecular cloud from which it was formed has nearly dissipated. Underhill & Bhatia (1988) postulate that ringlike disks, as described here, are formed around massive stars whenever larger than normal magnetic fields are occluded as the stars form. Only those stars which occlude sufficiently large magnetic fields generate a high electron temperature (approximately 10^5 K) by magneto-hydrodnamic processes which transform the mechanical energy present in the material from the molecular cloud to heat. A high electron temperature is needed to generate a Wolf-Rayet-type spectrum. The conditions necessary for forming a Wolf-Rayet-type spectrum have been inferred by Bhatia & Underhill (1986, 1988, 1990). Why a cooling, dense, spherical wind of anomalous composition is not an adequate source for a Wolf-Rayet spectrum has been noted by Underhill (1991, § 3).

The core of the Wolf-Rayet star may radiate a wind such that the rate of mass loss is of the order of a few times $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, cf. Underhill et al. (1990c), while the disk may generate a wind driven by magnetodynamic effects, cf. Gomez de Castro & Pudritz (1993). Both the stellar and the disk-driven winds as well as the plasma of the confined disk will radiate bremsstrahlung radiation. This fact may account for the relatively large radio fluxes observed from Wolf-Rayet stars in spite of their considerable distances (Underhill 1986). The observed radio fluxes are not necessarily due solely to a spherically symmetric wind from the core of the star moving at a constant velocity of outflow. Underhill for a long time, cf. Underhill (1968), has suspected that Wolf-Rayet stars and T Tauri stars have similar physical forms.

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