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AN 8 YEAR STUDY OF THE RADIO EMISSION FROM THE WOLF-RAYET BINARY HD 193793 = WR 140

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ABSTRACT

HD 193793 = WR 140 is a W-R+O binary system with a 7.9 yr, highly elliptical ($e = 0.85$) orbit. It shows variable, nonthermal radio emission over its orbital period that is explained as synchrotron radiation from relativistic electrons accelerated in the shock between the W-R and O winds. Although we now know of quite a few W-R+O star binary systems, only HD 193793 is well studied across the entire electromagnetic spectrum; hence, it affords us the best opportunity to test various models for the system against a wealth of observational data. HD 193793 is an ideal laboratory for studying the properties of hot star winds and the physics of particle acceleration by strong shocks in those winds.

In this paper we present the results of 8 years of monitoring the radio flux density from HD 193793 with the VLA. This database is unique both in terms of its dense coverage of an entire binary cycle and because it extends the radio coverage to 2 cm wavelength, a shorter wavelength than previously available. With these data we are able to simultaneously solve for the time-dependent attenuation in the system and the intrinsic radio luminosity. The standard model of spherically symmetric colliding winds faces severe difficulties in explaining the observations. We conclude that the radio data are most readily interpreted if we adopt a new model of the system in which the W-R star wind is strongly equatorially enhanced, so that most of the mass loss is confined to a plane. This model for the W-R wind also provides a natural explanation for the sudden formation of dust that causes an infrared outburst just after periastron.

Subject headings: binaries: spectroscopic — radio continuum: stars — stars: individual (HD 193793) — stars: Wolf-Rayet

1. INTRODUCTION

A significant number of W-R stars are known to reside in binary systems with O star companions. At least some of these systems have highly elliptical orbits ($e = 0.8$). Generally speaking, in these systems both stars exhibit mass loss, which in turn results in a variety of observable phenomena (van der Hucht et al. 1992). The most interesting of these arise from the interaction between the W-R and O star winds. These phenomena can vary wildly over a binary cycle as the interaction zone moves closer to or farther from the two stars.

Perhaps the best studied of these systems is HD 193793 (WR 140). In 1987, Williams et al. (1987) concluded that the two stars of HD 193793 (WC 6 and O6; McDonald 1947) had a 7.9 yr binary orbit based on two dust formation episodes which occurred near periastron (= phase 0). The orbit is highly elliptical, with an eccentricity of 0.85 (Williams et al. 1990; Annuk 1995; Fig. 1). From a number of observations it was clear that the radio emission from HD 193793 also varied dramatically over the binary period (Florkowski 1982; Becker & White 1985). At radio quiescence near phase 0.1, the emission appears consistent with the thermal free-free emission from the W-R star's ionized wind (which presumably dominates by a large factor over the O star wind). Later in the orbit the radio emission increases markedly and changes character, becoming primarily nonthermal. This nonthermal emission is generally accepted as arising from the interaction zone of the two winds. Considerable work has been centered on interpreting the phase dependence of the nonthermal radio emission (Williams et al. 1990; Eichler & Usov 1993). As early as 1984, it became apparent to us that the solution of this problem required a more detailed radio light curve. Starting in 1985, we began to monitor HD 193793 with the NRAO[1] Very Large Array (VLA) and continued to do so through 1993 August. In this paper, we present the results of the VLA monitoring program and use the observed light curve to constrain the geometry of the W-R wind and its interaction with the O star wind.

2. OBSERVATIONS

Approximately once a month for 8 years beginning in 1985 October, 1.5–2 hr of VLA time were allocated to observe HD 193793. Most of the observations were made at two wavelengths (2 and 6 cm) except for the time interval 1990 October to 1992 October when 20 cm was observed as well. The observations were made in standard continuum mode with 50 MHz bandpasses on two IFs. The observations were calibrated against either 3C 48 or 3C 286 as well as a nearby secondary calibrator. By necessity, the observations were made in all VLA configurations, resulting in a rather nonuniform data set. However, since nonthermal emission of HD 193793 is unre-

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

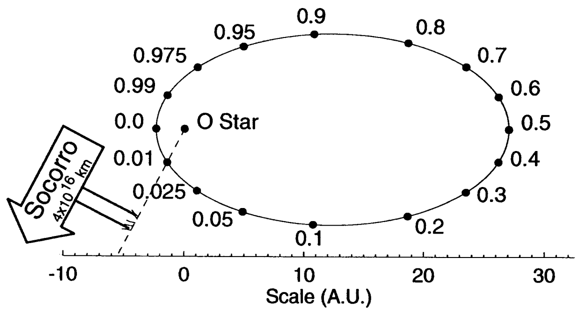

FIG. 1.—Orbit of HD 193793. The O star is located at the origin; the position of the W-R star as a function of phase is marked, as is the viewing direction.

solved by the VLA even in the A configuration, the measured flux densities should be configuration independent except during quiescence, when the dominant source of radio emission is thermal free-free emission. The data were calibrated, self-calibrated, and imaged using standard AIPS routines. The resulting light curves at 2, 6, and 20 cm are given in Table 1 and shown in Figure 2. We estimate an intrinsic uncertainty in the flux calibration of ~10%. The uncertainty is typically larger at 2 cm because the VLA receivers are noisier and water vapor in the atmosphere causes fluctuations; the additional scatter seen at 2 cm is probably the result of measurement error, not intrinsic variation. The same data are plotted in Figure 3 as a function of orbital phase. In Figure 4 the 2 cm and 6 cm flux densities are displayed as a shaded surface plot in which orbital phase increases in the counterclockwise direction and the vertical height is proportional to the flux density.

3. INTERPRETATION

The most striking aspect of the three light curves is their asymmetry with respect to periastron passage. Of equal interest, there is a strong frequency dependence to the light curves. The high-frequency emission rises earlier, peaks earlier, and begins to decay earlier than emissions at lower frequencies.

At a given frequency, the observed flux density will depend on the intrinsic luminosity of the nonthermal emission as well as the amount of attenuation suffered traversing the binary system. There seems little doubt that both quantities are time dependent. Consider the scenario in which both stellar winds are spherically symmetric. If attenuation were negligible, the intensity of the interaction should depend only on the separation of the two stars, and the light curve would be symmetric

TABLE 1

VLA OBSERVATION OF HD 193793

Date[a]	Config[b]	S_2[c]	S_6[c]	Date	Config	S_2	S_6	Date	Config	S_2	S_6	S_{20}[c]
01/20/85	A	3.3	1.1	12/17/87	B	9.6	2.2	09/03/90	B	19.3	21.9	...
06/26/85	B/C	...	1.6	01/21/88	B	9.1	3.0	10/02/90	B/C	16.4	20.6	7.2
10/05/85	C	3.4	2.1	02/22/88	C/D	...	2.4	11/18/90	C	21.9	22.4	...
10/15/85	C	3.5	1.8	03/08/88	C/D	11.3	3.2	12/03/90	C	17.8	20.8	7.8
10/19/85	C	3.8	2.0	04/09/88	C/D	9.1	3.4	02/21/91	C/D	20.0	26.8	...
10/23/85	C	3.9	2.1	05/14/88	C/D	11.6	3.7	03/16/91	D	20.6	28.1	...
10/25/85	C	3.9	2.1	06/19/88	C/D	9.3	3.9	04/07/91	D	22.1	26.8	...
10/26/85	C	4.2	1.9	07/29/88	D	...	4.1	05/10/91	D	18.5	25.9	...
10/27/85	C	4.1	2.0	08/25/88	D	10.4	4.3	06/27/91	A	18.5	23.8	15.5
10/28/85	C	4.2	2.2	09/27/88	D	13.7	4.6	07/25/91	A	17.6	27.8	18.7
10/29/85	C	4.3	2.1	11/19/88	A	11.2	4.4	08/24/91	A	17.7	24.5	19.2
10/30/85	C	3.9	2.2	12/02/88	A	12.2	4.5	09/08/91	A	18.5	25.7	19.5
10/31/85	C	4.9	2.1	01/07/89	A	...	5.1	10/16/91	A/B	13.0	26.1	22.9
11/06/85	D	4.8	1.4	02/17/89	B	12.8	6.0	11/22/91	B	13.5	25.3	24.1
11/21/85	D	3.8	2.0	03/11/89	B	12.8	5.7	12/20/91	B	13.1	23.1	24.2
12/13/85	D	6.5	...	04/23/89	B	16.6	7.1	01/16/92	B	14.8	25.4	20.8
12/22/85	D	5.3	1.9	05/14/89	B/C	16.8	7.9	02/16/92	B/C	11.7	...	21.5
01/28/86	D	4.6	2.0	06/15/89	C	16.3	6.9	03/05/92	C	12.4	20.5	19.4
02/28/86	A	3.6	1.5	07/24/89	C	15.3	8.2	04/06/92	C	14.9	21.4	20.1
03/19/86	A	2.9	1.5	08/06/89	C	...	9.0	05/12/92	C	13.1	17.5	15.2
04/17/86	A	...	1.4	09/30/89	C	17.0	10.2	06/14/92	C/D	9.9	15.2	11.1
06/10/86	A	4.0	1.9	10/09/89	C/D	15.8	9.1	08/06/92	D	13.2	11.8	8.0
06/24/86	A/B	5.4	1.9	11/13/89	D	17.0	11.6	09/17/92	D	8.2	8.6	4.9
07/23/86	B	5.3	2.1	12/23/89	D	18.5	13.4	10/22/92	A	5.2	5.3	2.2
08/24/86	B	5.2	1.5	01/14/90	D	18.8	12.6	11/21/92	A	4.6	3.0	...
09/13/86	B	6.4	2.4	02/05/90	D/A	...	11.2	12/12/92	A	3.1	2.1	...
10/15/86	B/C	6.0	2.1	02/12/90	A	19.3	13.6	01/23/93	A	2.0	1.5	...
11/20/86	C	7.1	2.3	03/03/90	A	20.9	15.4	03/06/93	B	3.2	1.5	...
12/24/86	C	5.6	2.2	03/19/90	A	17.1	16.1	04/09/93	B	3.7	1.6	...
01/16/87	C	5.1	2.3	04/02/90	A	17.4	14.9	05/04/93	B	4.6	1.2	...
02/05/87	C/D	6.4	2.3	05/16/90	A	19.0	17.0	06/08/93	B/C	4.1	1.4	...
04/28/87	D	6.6	2.7	06/13/90	A	20.0	20.7	07/10/93	C	3.7	2.1	...
05/11/87	D	7.8	2.8	07/01/90	A/B	19.3	19.4	08/17/93	C	2.9	1.9	...
06/06/87	D	8.4	2.7	08/01/90	B	17.1	20.3					

[a] Date of observation in format month/day/year.
[b] Configuration of VLA (A, B, C, D, and transitions between these configurations).
[c] Flux densities at 2, 6, and 20 cm are given in milliJanskys.

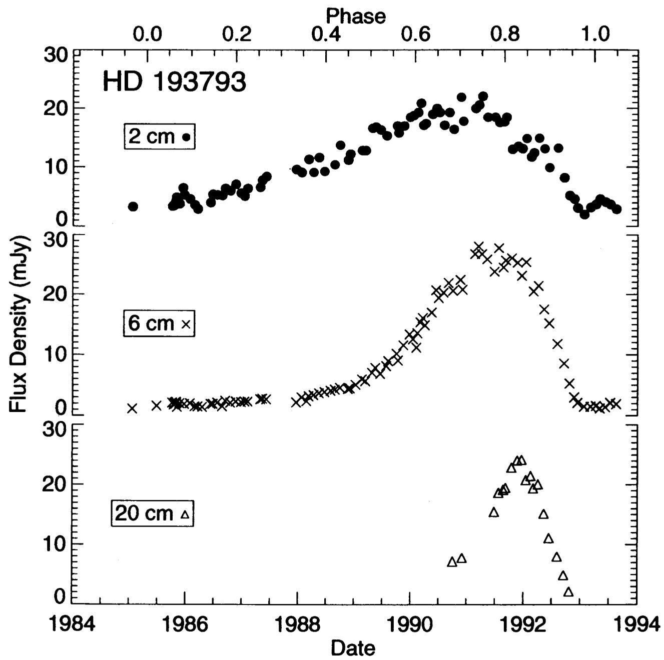

FIG. 2.—Radio flux density of HD 193793 at 2, 6, and 20 cm as determined from our VLA monitoring program. Top axis shows the phase of the orbit, with phase 0 (at 1985.3) being periastron. The orbital period is 7.94 yr.

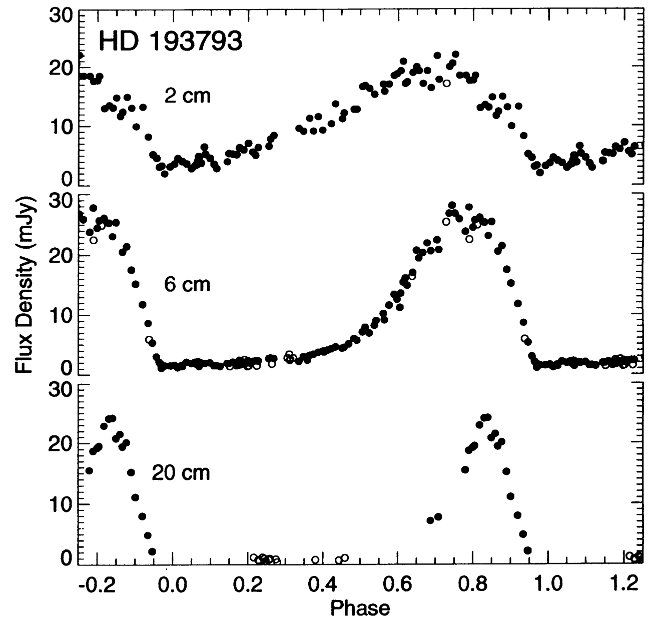

FIG. 3.—Radio flux density of HD 193793 at 2, 6, and 20 cm as a function of orbital phase. Our data are shown with filled symbols, and data drawn from the literature (Williams et al. 1990) are shown with open symbols. Note the excellent agreement with the other data, which in most cases were not taken during the 1985–1993 cycle. The radio emission repeats almost perfectly from cycle to cycle.

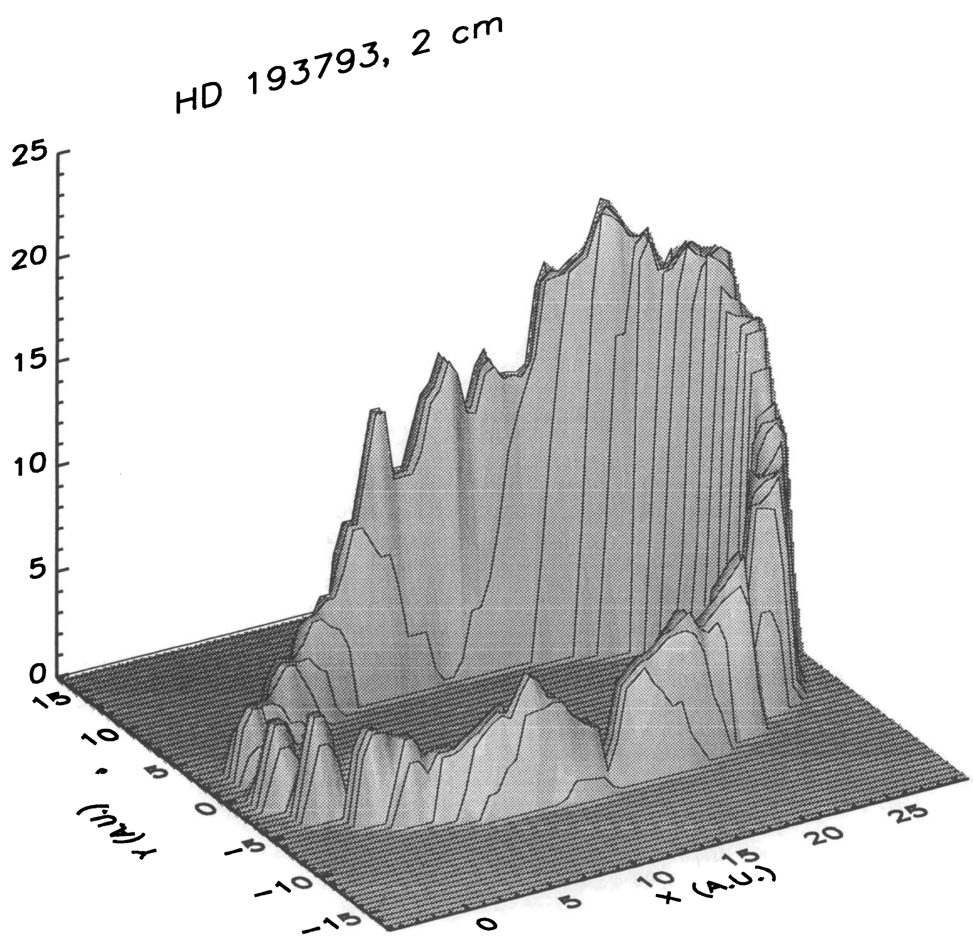

FIG. 4*a*

FIG. 4.—Radio flux density of HD 193793 at 2 and 6 cm shown as a function of position in the orbit. Phase increases counterclockwise around the orbit, as shown in Fig. 1.

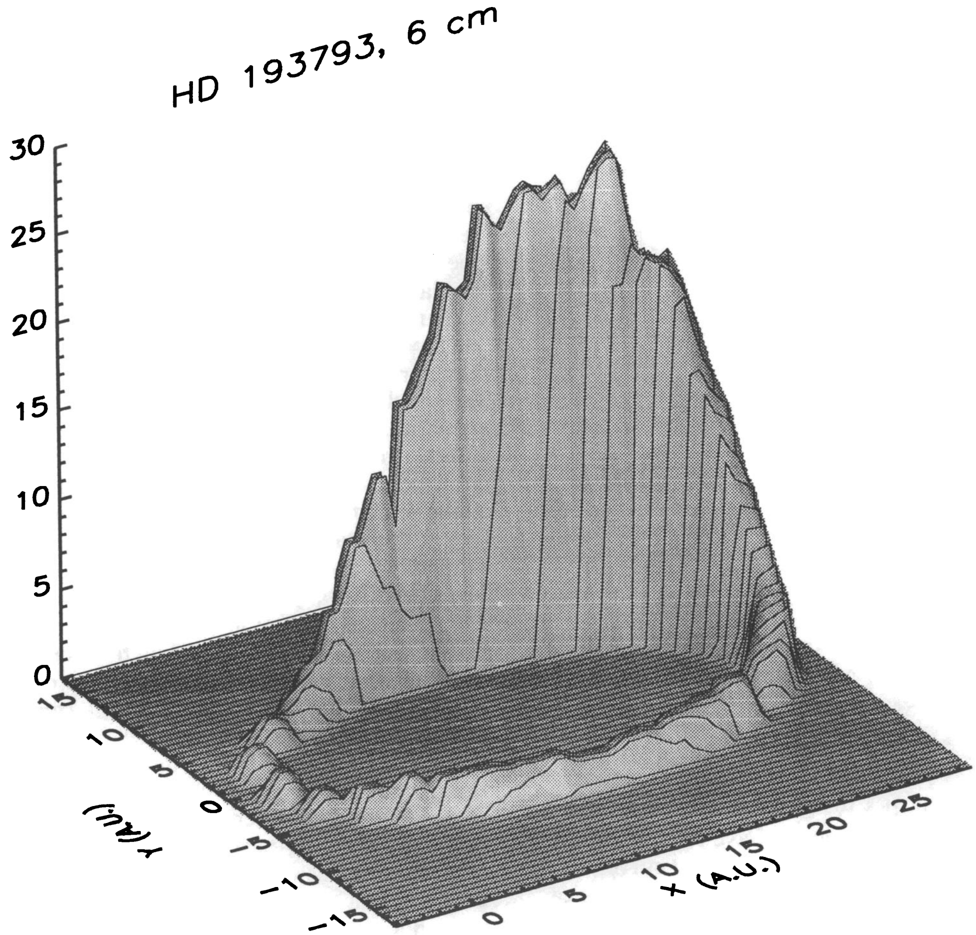

FIG. 4b

about phase 0.5. However, strong attenuation will most certainly exist because of free-free absorption in the winds. For example, van der Hucht (1991) estimates the radio photosphere of the W-R star's wind to have radii of 20, 41, and 101 AU at 2, 6, and 20 cm, respectively. With these large radii one would hardly expect to see radio emission even at 2 cm when viewing the emission region through the W-R wind. Williams et al. (1990) also calculated the light curve, taking attenuation by the W-R star's wind into account (his Fig. 13), but still found poor agreement with observations. In particular, although less symmetric, the derived light curve still overestimated the radio flux density between phases 0.2–0.5.

Williams et al. (1990) concluded that the light curve could not be reproduced using a model of spherically symmetric winds and suggested a more complex model that included a hole in the W-R star's wind in the O star's shadow. When the hole is oriented along our line of sight the attenuation will be greatly reduced. This model was subsequently elaborated by van der Hucht (1991) and Eichler & Usov (1993). Clearly, the radio light curve predicted by the model will depend strongly on the exact geometry of the shadow cast by the O star. While this model is appealing in its simplicity and qualitatively would appear to explain the gross shape of the radio light curves, we find that quantitatively it fails to correctly predict the light curves shown in Figures 2 and 3.

In particular, we would call attention to the light curves near phase 0.8. By the time the 20 cm flux density peaks at phase 0.85, the 2 cm light curve has already fallen by nearly 50% from its peak. In other words, the 2 cm flux density is falling while the 20 cm flux density is rising. If the emission mechanism is not changing, i.e., if the spectral index is fixed, then we concluded that from phase 0.7 to 0.85 the intrinsic luminosity is falling at both 2 and 20 cm but that the attenuation at 20 cm is falling even faster. If we assume a constant spectral index, then we can estimate both the optical depth and intrinsic luminosity as a function of time from the relative flux densities at 2, 6, and 20 cm. Using a spectral index $\alpha = -0.5$ ($F_\nu \propto \nu^\alpha$), the derived attenuation and intrinsic luminosity as a function of phase are shown in Figure 5.

To successfully explain the variation in Figure 5, a model will have to explain a decrease in the intrinsic luminosity after phase 0.7 and a simultaneous sharp drop in the attenuation. These variations are very difficult to accommodate in the context of spherically symmetric winds (SSWs). Generally, we assume that the shocks that generate the nonthermal radio emission become stronger in the SSW model as the two stars approach each other. Yet the 2 cm flux density implies that the interaction is decreasing after phase 0.7. Likewise, the abrupt drop in the free-free attenuation at phase 0.8 is inconsistent with spherical winds and can be rationalized only in SSW

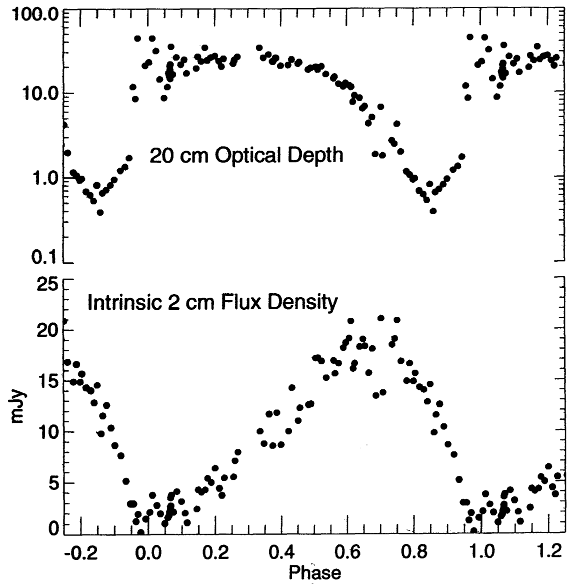

FIG. 5.—Optical depth at 20 cm and intrinsic 2 cm flux density (nonthermal component only, before attenuation by free-free absorption) as a function of phase. Any radio emission buried below the 2 cm photosphere is not represented. Derived by fitting 2, 6, and 20 cm flux densities using a nonthermal spectrum $F_\nu \propto \lambda^{0.5}$, free-free absorption with $\tau(\lambda) \propto \lambda^{2.1}$, and a stellar wind spectrum with $F_\nu = 1$ mJy $(\lambda/6\ \mathrm{cm})^{-0.6}$.

models with a large hole in the W-R star's wind caused by a shadow of the O star. Such a hole would have to be very wide and have a curved surface to explain the radio light curves.

In fact, the observation of *any* 20 cm emission is not explicable by this model regardless of the size and shape of the hole in the W-R wind. Figure 6 shows the regions of the winds that are blocked from our view (optical depth $\tau > 1$) by free-free absorption in the W-R and O winds. Along a radial line of sight, optical depth unity at 20 cm wavelength is reached at 95 AU from the W-R star and 8 AU from the O star. The optical depth increases very rapidly as one gets closer to the star ($\tau \propto 1/r^3$), so the shadow is relatively sharp edged.

If there is a hole in the W-R wind then, we are looking through the much reduced absorption of the O wind; however, it is obvious from the figure that the O wind alone has such a large optical depth at 20 cm that we cannot expect to see a significant amount of 20 cm emission at phase 0.83. The only way around this objection is to move the radio-emitting region farther from the O star so that it is not blocked by the O wind. This cannot be accomplished by changing the mass loss rate for the O star because a larger $\dot{M}$ leads to more 20 cm absorption and a smaller $\dot{M}$ causes the shock to collapse toward the O star.

4. A NEW MODEL

We suggest that the radio data can be more naturally explained if the W-R star's wind is mainly confined to a plane (presumably the star's equatorial plane) that is tilted with respect to the orbital plane of the stellar system. Since the wind velocity is large compared to the W-R star's orbital velocity, this "sheet" of material will follow the W-R star as it moves in its orbit. Twice an orbit, this sheet will sweep across the position of the O star. When the O star is behind this curtain of gas, the high free-free opacity will cut off the radio emission. When the O star is in front of the curtain, the opacity to the radio-emitting region will be low.

In this scenario, the strength of the nonthermal emission will depend mainly on the distance of the O star from the equatorial plane of the W-R star rather than its distance from the W-R star itself. The observed peak in the radio at phase 0.7 indicates the passage of the O star through the W-R wind plane. This model provides a natural explanation for the sudden drop in opacity after phase 0.7. In fact, the rapidity of the drop in opacity must be telling us that the sheet of material is relatively thin even 20 AU away from the W-R star.

This model does introduce some new complexities. The shock boundary between the two winds spreads out over a large area of the surface of the W-R star's planar wind. Hence the shock is seen over a range of densities through a range of opacities. As a result, a fairly sophisticated model will be needed to duplicate the observed radio data. Furthermore, the W-R wind is certainly not totally confined to the equatorial plane, but must have a roughly isotropic component as well. When the stars are close together, the O star wind will be stopped by this lower density wind before it reaches the dense equatorial flow, which will affect both the radio emission and the opacity as a function of phase.

The disk model, if correct, will have important ramifications at other wavelengths. In particular, the disk model provides a natural explanation for the sudden formation of dust shortly after periastron (Williams et al. 1990). It is near periastron that the O star enters the W-R wind disk for a second time, but in this passage it is much closer to the W-R star and sees a correspondingly higher wind density (by a factor of several hundred) over the passage at phase 0.7. The O star's introduction into this environment triggers the dust formation. In contrast, in a model assuming spherical winds, it must be considered a remarkable coincidence that periastron passage corresponds to the critical density needed for dust formation. Figure 7 shows the variation of the W-R wind density at the location of the O star with phase expected from the spherical wind model. Although the density does sharply increase at phase zero, the occurrence of the infrared outburst (also shown in the figure) no earlier than phase zero can be explained only if the density at periastron exceeds the critical density for dust formation by less than a factor of 2. In the wind disk model, however, the O star passes through the W-R disk at phase $\sim$0.002, encountering a much higher density there than at slightly earlier phases. Even if the density at midplane passage is many times the critical density for dust formation, the density just outside the disk will be too low for dust to form.

This new model has striking implications for W-R winds. HD 193793 is such a widely separated binary that the wind from the W-R star is barely affected by the presence of the O star. Presumably, all similar W-R stars, single or binary, also have equatorially enhanced winds. Polarization observations have previously led to the suggestion that at least some W-R winds are not spherically symmetric (Schulte-Ladbeck, Meade, & Hillier 1992); we believe the results presented in this paper to be the strongest evidence yet for gross deviations from spherical symmetry in W-R winds. Cassinelli, Ignace, & Bjorkman (1995) propose a model in which the combination of modest rotation and a slowly accelerating wind naturally lead to equatorially enhanced mass loss in W-R winds.

Other W-R + O binary systems might have dramatically different observational characteristics depending on the relative orientations of the wind plane and the orbital plane. If the two

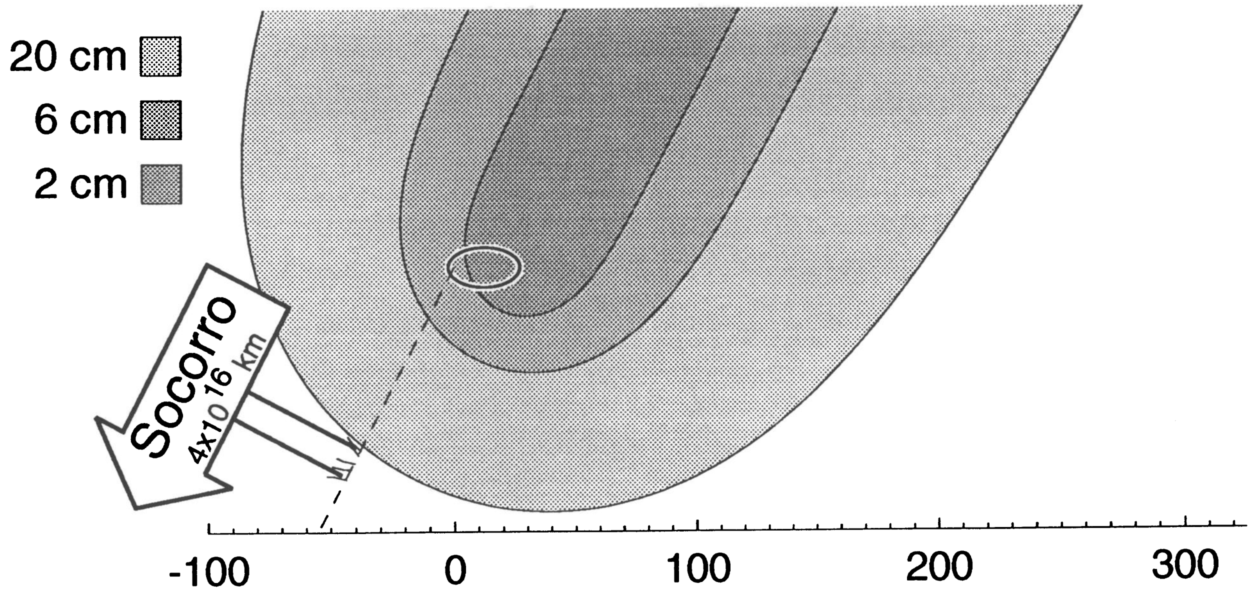

FIG. 6*a*

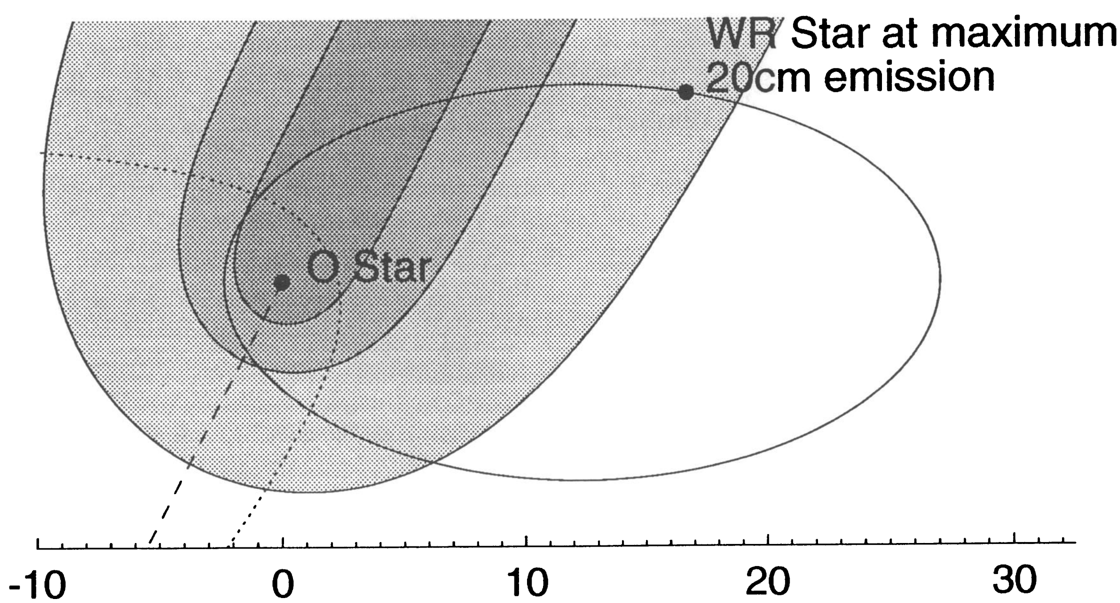

FIG. 6*b*

FIG. 6.—Free-free absorption by O and W-R winds in HD 193793. Orbit and viewing direction are shown. The shaded areas are blocked from our view ($\tau > 1$) in the spherical wind model by free-free absorption at 2, 6, and 20 cm. *Left*: Large-scale view showing W-R absorption at widest separation. Note that the wind interaction is entirely hidden at 6 cm and 20 cm. *Right*: Small-scale view showing O absorption at phase of maximum 20 cm emission. The position of the shock, computed using the analytical model from Stevens, Blondin, & Pollock (1992), is shown by the dotted line. Even if there is a hole in the W-R wind, the O wind absorption would prevent us from observing much 20 cm emission.

planes were to coincide, the O star would always be immersed in the W-R wind; much of the radio emission would consequently be absorbed, and variations with orbital phase would be much less dramatic than for HD 193793. Alternatively, if the wind plane were oriented such that the O star crossed the disk at phases 0.98 and 0.02, then for a favorable viewing angle the radio emission would be visible through most of the orbit. In addition, there would be two closely spaced dust formation episodes. Hence, other W-R binary systems could show radically different light curves from HD 193793 and yet still be explained by a similar model.

We gratefully acknowledge the long-term support of Barry Clark, who without fail scheduled this project on the VLA every month for 8 years. An earlier version of this paper was presented at IAU Symposium No. 163 in Elba, Italy, where we greatly benefited from our interactions with other conference participants.

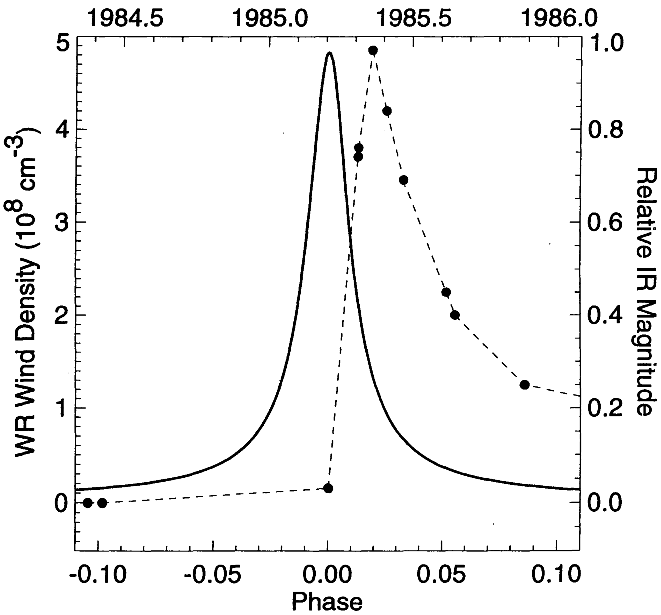

FIG. 7. Spherical wind model prediction for phase variation of the W-R wind density at the location of the O star. The dots show infrared H (1.6 μm) measurements from Williams et al. (1990) made during the 1985 outburst. The orbital elements from Annuk (1995) have been used to set the time of phase zero. The infrared outburst began at or shortly after periastron. This is naturally explained by the wind disk model, but the spherical model would require that the wind density exceed the critical density for dust formation by less than a factor of 2 at phase zero.

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