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# SPECTROSCOPIC STUDIES OF O-TYPE BINARIES. V. THE Of SYSTEM HD 166734

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## ABSTRACT

Spectroscopic data we have obtained over seven years enable us to determine an orbit for HD 166734, which is found to be a double-lined binary system with components O7.5 If and O9 I of similar luminosity and mass. Its evolutionary state is briefly discussed.
*Subject headings:* stars: binaries — stars: early-type — stars: individual

## I. INTRODUCTION

HD 166734 was announced to be a double-lined spectroscopic binary by Wolff (1963), who noted single and double absorption lines on two separate coudé spectrograms obtained by Herbig at the Lick Observatory. He found emission lines at λλ4634, 4640 N III and λ4686 He II, as did Conti and Alschuler (1971), who classified the (combined) type as O7.5 If from a single-lined spectrogram. Walborn (1973) noted double lines and classified the individual stars as O7 Ib(f) plus O8–O9 I. Observations on HD 166734 were begun by P. S. C. at the Lick Observatory in 1971 and have continued up to the present. The data are now sufficient to obtain for the first time an orbit for this luminous and highly evolved system.

In § II we discuss the observational data and the reduction procedure followed. The orbit is derived in § III, and a discussion of the physical parameters of the system is found in § IV. Some conclusions about the evolutionary state of this binary are discussed in § V.

## II. OBSERVATIONS AND REDUCTIONS

The observations were carried out during 1971–1978 using eight telescopes in two hemispheres. The spectrograph data are summarized in Table 1. In general, the Cassegrain plates were measured by V.S.N. using the Grant oscilloscope comparator at La Plata Observatory, while the coudé plates were measured by D.E. on the Grant comparator at NBS and JILA. A few of the coudé plates were also measured at La Plata. The last few coudé plates (D7860–D8153) were obtained with a two-stage "advanced Carnegie" design image-tube camera and were measured by P.M. for radial velocities from scans made with a PDS series 1000 microphotometer belonging to HAO, using a procedure described elsewhere (Massey 1980). The typical projected slit width was 20–25 μm at the plate. There appears to be no systematic difference between the measuring methods. The Journal of Observations is given in Table 2. The slightly brighter star is called the primary (§ IV).

The laboratory wavelengths were taken from Moore (1945). Typically the Balmer lines Hγ through H11, He I λ4471, and He II λ4200, λ4541 were used for the averages from the blue plates. Averages for the red exposures were obtained from He I λ5876 and the C III λ5696 emission line. Although real differences could exist in the velocities of these lines since they are formed in different regions, the data are not good enough to comment on this even qualitatively, except to say that the differences are not large. The agreement between lines was usually less than $\sim 30$ km s$^{-1}$ for the double-lined plates and slightly worse for the single-lined plates.

The long period and high eccentricity necessitated using whatever instrumentation was available to the authors during their various observing runs to obtain enough data for an orbit solution. Despite the large differences in equipment and dispersions, the agreement of plates taken at the same phase is excellent. It is true that the lower dispersion and the image tube material occasionally showed indistinct, wide, single lines at phases for which the coudé plates revealed clearly double lines, as might be expected. Although the velocity separation at periastron is so great ($>400$ km s$^{-1}$) that the lines are readily measurable

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TABLE 1

SPECTROGRAPH DATA

| Plate Code | Observatory | Telescope (m) | Spectrograph | Emulsion | Dispersion (Å mm$^{-1}$) |
|---|---|---|---|---|---|
| A | CTIO | 0.9 | Cassegrain | IIa-O | 124, 60 |
| C | CTIO | 1.5 | Cassegrain | IIa-O | 38 |
| D + 3 digits | CTIO | 1.5 | coudé | IIa-O | 18 |
| | | | | 098-04 | 18 |
| D + 4 digits | KPNO | 2.1, 0.9 | coudé | IIa-O | 17 |
| | | | | 098-04 | 25 |
| D7860–D8153 | KPNO | 0.9 | coudé ITS | IIIa-J | 10 |
| I | Bosque Alegre | 1.5 | Cassegrain | IIa-O | 42 |
| EC | Lick | 3 | coudé | IIa-O | 16 |
| Ce | Mount Wilson | 2.5 | coudé | IIa-O | 20 |
| Pd | Palomar | 5 | coudé | IIa-O | 18 |

on all plates taken near that phase, at other times blending is a problem and the coudé material was crucial in determining the orbit. Accordingly we have given the Cassegrain observations less weight in what follows.

## III. THE ORBIT

The period proved to be difficult to determine despite the large number of observations. Data spanned 7 years, yet they never covered more than $\sim 10$ days at a time, and the velocities never changed substantially between plates except during one run when the system passed through periastron. A further complication was the fact that the two components are of similar spectral type and luminosity, and their spectra are hard to disentangle. Consequently it was not possible to assign velocities to each component until the period could be determined.

We used a period-finding program based on the method of Lafler and Kinman (1965), but used the velocity difference between the two stars rather than the individual velocities. For a system with a noncircular orbit, a plot of the velocity difference with phase will show two unequal humps and so should yield a unique period with this method; a circular orbit would contain two equal humps, and the program would produce multiples of the correct period. The period was found from the coudé data alone. (We also included the velocity difference determined from D7042 [JD 2,443,318.81, $\Delta V = 370$ km s$^{-1}$], which was taken near periastron but which unfortunately contained no comparison lines.) One strong minimum was found, at 34.56 days. This period was used to assign phases to the plates, and by inspection of the resulting velocity-phase points we were able to associate the individual velocities with the appropriate star. A tracing of the very widely separated double-lined EC 1284 (JD 2,437,861.75, $\Delta V = 350$ km s$^{-1}$), which was the "discovery plate" taken by Herbig, was then used to refine the period to 34.54 days. Despite the fact we used only the coudé plates to determine the period, all the other observations fit nicely as well, indicating we indeed have the correct period.

Two entirely independent orbit solutions were computed: one by classical graphical methods and the other by the standard method of differential corrections. Since the velocity-phase diagram showed that the eccentricity was high, we felt that it would be best to determine the orbital elements by these two different means. Although the differential correction technique will give a "best" solution, experience has shown us that the exact value of the orbital parameters—particularly the eccentricity—is a critical function of what data are included. A large change in the value for $e$ is necessary to appreciably affect the computed velocity curve. Happily both methods produced essentially the same results. The elements are given in Table 3, and the orbit solution is shown in Figure 1. $T$ is the time of periastron passage.

The "anomaly diagram" method of Russell (1914) requires only that the period be known in advance. Essentially, one computes the angular position of the star in its orbit (the true anomaly) and compares this angle to that which would be expected if the orbit were circular. For an eccentric orbit the difference varies as one cycle of a sinusoid across the orbital cycle. The amplitude of the sinusoid is directly related to the eccentricity, and the axis of symmetry defines $\omega$. The velocity amplitudes and the $\gamma$-velocity can then be computed. The method uses data from both stars at the same time and implicitly constrains the orbital elements of the two stars to have the relation expected physically: i.e., the same $e$, $\omega$ that differ by 180°, and the same $\gamma$-velocity. This last condition, that the $\gamma$-velocities are necessarily equal for the two stars, is known to be incorrect for binaries containing Of stars, such as BD +40°4220 and HDE 228766 (Massey and Conti 1977). The difference in $\gamma$-velocities is evidence of stellar wind outflow even at the deep layers where the lines are formed.

The program for computing orbits by differential corrections is based on the program described by Wolfe, Horak, and Storer (1967) and subsequently modified at the University of Colorado by Mr. Paul Barker and P. M. The orbit for each star is computed separately, and we list these values in Table 3 along

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TABLE 2

JOURNAL OF OBSERVATIONS HD 166734

| Plate | JD 2440000+ | φ | Radial Velocities (km s$^{-1}$) Secondary | Primary | Single |
|---|---|---|---|---|---|
| EC 9633 | 1136.91 | 0.82 | +106 | -81 | |
| EC 9723 | 1164.76 | 0.62 | -35 | +14 | |
| Ce 21064 | 1458.83 | 0.14 | -96 | +87 | |
| Ce 21070 | 1459.82 | 0.16 | -76 | +100 | |
| D 187 | 1491.74 | 0.09 | | | -62 |
| A 2309 | 1492.73 | 0.12 | -64 | +75 | |
| A 2314 | 1493.65 | 0.14 | -65 | +43 | |
| Ce 21192 | 1494.70 | 0.17 | -95 | +105 | |
| Ce 21198 | 1495.72 | 0.20 | -88 | +83 | |
| Ce 21204 | 1496.72 | 0.23 | | | -19 |
| Ce 21208 | 1497.72 | 0.26 | | | -13 |
| I 8424 | 1552.50 | 0.85 | | | -35 |
| Pd 13070 | 1586.67 | 0.84 | +116 | -95 | |
| Pd 13074 | 1587.65 | 0.87 | +114 | -129 | |
| A 2617 | 1823.92 | 0.71 | +32 | -36 | |
| A 2624 | 1827.88 | 0.82 | +102 | -93 | |
| A 2631 | 1828.86 | 0.85 | +99 | -110 | |
| A 2636 | 1829.90 | 0.88 | +131 | -105 | |
| A 2641 | 1909.65 | 0.19 | -74 | +96 | |
| A 2644 | 1910.62 | 0.22 | | | +17 |
| A 2653 | 1912.57 | 0.27 | | | +3 |
| A 2656 | 1912.67 | 0.28 | | | +32 |
| C 3266 | 1915.69 | 0.36 | -110 | +55 | |
| D 3860 | 1934.66 | 0.91 | +166 | -223 | |
| D 3864 | 1935.66 | 0.94 | +208 | -236 | |
| D 3870 | 1936.68 | 0.97 | +175 | -193 | |
| D 3876 | 1937.66 | 0.00 | +133 | -130 | |
| D 4758 | 2289.72 | 0.19 | -90 | +58 | |
| D 4765 | 2290.67 | 0.22 | -60 | +70 | |
| A 4109 | 2473.90 | 0.52 | | | -96 |
| D 5415 | 2567.89 | 0.25 | -105 | +89 | |
| A 4430 | 2878.85 | 0.25 | | | -3 |
| A 4435 | 2879.89 | 0.28 | -90 | +95 | |
| A 4445 | 2881.86 | 0.34 | | | -4 |
| A 4451 | 2882.80 | 0.36 | | | -6 |
| D 714 | 2882.86 | 0.36 | -85 | +43 | |
| D 730 | 2888.88 | 0.54 | -62 | +16 | |
| D 736 | 2889.87 | 0.57 | -49 | +13 | |
| D 743 | 2890.88 | 0.60 | -33 | +12 | |
| D 7048 | 3320.87 | 0.05 | +115 | -83 | |
| C 4851 | 3357.75 | 0.11 | -85 | +99 | |
| C 4855 | 3358.64 | 0.14 | -64 | +114 | |
| C 4858 | 3359.67 | 0.96 | -64 | +128 | |
| A 4764 | 3362.68 | 0.26 | | | +17 |
| A 4766 | 3363.60 | 0.28 | | | -15 |
| D 7134 | 3394.67 | 0.18 | -80 | +73 | |
| D 7145 | 3398.71 | 0.30 | -53 | +102 | |
| D 7860 | 3696.73 | 0.93 | +192 | -190 | |
| D 7884 | 3717.79 | 0.54 | | | +7 |
| D 7887 | 3718.79 | 0.57 | | | -7 |
| D 7894 | 3721.79 | 0.65 | | | -5 |
| D 7896 | 3723.78 | 0.71 | | | -11 |
| D 7986 | 3750.72 | 0.49 | | | +18 |
| D 8001 | 3753.65 | 0.58 | | | -3 |
| D 8141 | 3794.64 | 0.76 | | | +1 |
| D 8153 | 3796.63 | 0.82 | +79 | -59 | |

TABLE 3

ORBITAL ELEMENTS OF HD 166734

| Element | Graphical Solution Secondary | Graphical Solution Primary | $P = 34^d.54$ (adopted) Differential Corrections Secondary | Differential Corrections Primary | Adopted Secondary | Adopted Primary |
|---|---|---|---|---|---|---|
| $\gamma$ (km s$^{-1}$) | −4 | −4 | +2 ± 3 | −8 ± 3 | +2 | −8 |
| $K$ (km s$^{-1}$) | 154 | 168 | 140 ± 4 | 148 ± 5 | 140 | 148 |
| $e$ | 0.50 | 0.50 | 0.42 ± 0.03 | 0.50 ± 0.03 | 0.46 | 0.46 |
| $\omega$ | 40° | 220° | 44° ± 5° | 224° ± 4° | 44° | 224° |
| $T$ (2,440,000+) | 1005.12 | 1005.12 | 1005.37 ± 0.39 | 1004.98 ± 0.23 | 1005.12 | 1005.12 |
| $\sigma$ (km s$^{-1}$) | ... | ... | 13 | 15 | ... | ... |

with the formal probable errors. Only the double-lined plates are included in determining the orbital elements, and the Cassegrain plates have been given half weight. The quantity $\sigma$ is the standard deviation of the fit, as defined by Wolfe *et al.* for their quantity "R1." We note that the elements that are expected to be the same for the two stars all agree to within one probable error, except $e$, which differs by slightly more than that. The $\gamma$-velocities seem to differ significantly, with the less-massive star having the more negative velocity and hence stronger wind.

## IV. SPECTRAL TYPES AND PHYSICAL PARAMETERS

In order to determine spectral subtypes and assign luminosity classes to the two stars, the best double-lined plates were traced with the PDS microphotometer. The lines were too blended, except near periastron, to determine reliable equivalent widths, so our analysis suffers from using plates near one phase only. The stars are of nearly equal brightness as measured from the depths of the H9 lines, with the somewhat earlier star being slightly more luminous ($\lesssim 0.4$ mag). We have called this earlier star the primary, although the orbit solution presented in § III reveals that it is the less massive of the two.

The equivalent widths of He I $\lambda4471$ are 300 mÅ for the primary and 260 mÅ for the secondary; the values for He II $\lambda4541$ are 310 mÅ and 100 mÅ, respectively, where these values have not been corrected for the continuum contribution of the other star. Using the scheme of Conti (1973), we assigned spectral types of O7.5 for the primary, and O9 for the secondary, with an uncertainty of one subtype for each. These are similar to those quoted in the literature. The basic luminosity indicator for O stars is the Si IV $\lambda4098$ to He I $\lambda4143$ ratio (Conti and Alschuler 1971). Si IV $\lambda4089$ is quite strong in each star ($\sim 300$ mÅ) (but He I $\lambda4143$ is so weak that it is not measurable). We conclude that both these stars are supergiants.

There are broad, variable emission features always present at $\lambda\lambda4634$, 4640 N III, $\lambda4686$ He II and at H$\alpha$. Measures of the radial velocities of these lines by D. E. suggest the major contribution to each feature arises from the primary star. The actual velocity is correctly phased but is displaced redward by between 50 and 100 km s$^{-1}$. An emission contribution from the secondary star to each of these features cannot be excluded. On the other hand, narrow C III emission at $\lambda5696$ is clearly present in both stars and readily measurable near periastron (particularly on the first six listed "D" spectrograms). The velocities agree reasonably well with the absorption line velocities for these phases. The presence of C III emission in both stars is consistent with a conclusion that they are both quite luminous, $M_v < -6$: (Conti 1973). The conclusive presence of $\lambda4686$ He II emission in the primary, leads us to deduce

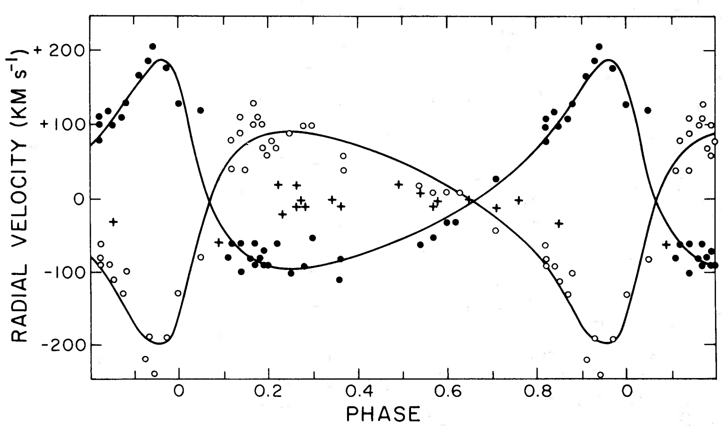


FIG. 1.—HD 166734: The open circles denote the primary and the filled circles the secondary. The crosses show the velocities from the single-lined plates, which were not used in calculating the orbit. The velocity curves drawn are from the adopted solution (Table 3) with a period of $34^d.54$.

it is an "f" type, following Walborn (1971) and Conti and Leep (1974).

From the observed $V$, $B - V$ of 8.42 mag and +1.07 mag (Johnson 1965) of the system, we compute individual magnitudes of 9.0 mag and 9.4 mag using the magnitude difference derived above. If we assume that the primary has an $M_v$ of −7 mag appropriate for its spectral type, we derive a modulus of 11.9 mag and a distance of 2.3 kpc. HD 166734 is not listed in any OB association discussed by Humphreys (1978), so this distance cannot be independently checked.

Using the adopted elements in Table 3, we compute the physical parameters of the system in Table 4. The minimum masses are 29 and 31 $M_{\odot}$. Note that the earlier type primary is slightly less massive than its companion. From the spectral types, we would anticipate masses of $\sim 50$ $M_{\odot}$ based on conservative evolution tracks and the tabulation of Conti (1975). If significant mass loss has occurred, the expected values could well be much lower. In this case the orbital inclination $i$ could be near to 90°, and eclipses might be observed. None have been reported, but the ephemerides given by our orbital elements will, we hope, prompt further investigations.

The line broadening $v \sin i$ (assumed due entirely to rotation) has been estimated by eye from comparison with some of the standard stars listed by Conti and Ebbets (1977). The resultant values, $\sim 80$ km s$^{-1}$ for each star seem to be much too high to be consistent with synchronous rotation with the relatively long orbital period. This observation and the observed orbital eccentricity would not support a suggestion that appreciable mass *exchange* has occurred in this system. On the other hand, a present mass-loss rate of $\sim 10^{-5}$ $M_{\odot}$ yr$^{-1}$ can be inferred from the H$\alpha$ emission line strength and the formulation of Klein and Castor (1978). This estimate is, of course, very rough.

TABLE 4

PHYSICAL PARAMETERS OF HD 166734

| Spectral Type | Primary (O7 If) | Secondary (O9 I) |
|---|---|---|
| Radius ($R_{\odot}$) | 23 | 24 |
| $V$ | $9^{m}.0$ | 9.4 mag |
| $M_v$ | $-7^{m}.0$ (assumed) | −6.6 mag |
| Distance (kpc) | 2.3 | 2.3 |
| $v \sin i$ (km s$^{-1}$) | 80 | 80 |
| $f(m)$ ($M_{\odot}$) | 8.1 | 6.9 |
| m $\sin^3 i$ ($M_{\odot}$) | 29 | 31 |
| a $\sin i$ ($M_{\odot}$) | 90 | 85 |

## V. CONCLUSIONS

We have derived an orbit for the relatively massive and luminous system HD 166734. The star with the higher observed mass-loss rate (from the emission line strength and the violet-shifted absorption line $\gamma$-velocity) is of earlier spectral type, somewhat brighter and slightly less massive. The minimum masses are such that the orbital inclination could be large, and eclipses might be expected if considerable mass loss has already occurred in this system.

From the spectral types, the strengths of the Si IV absorption, and the presence of $\lambda$5696 C III emission in both stars, we conclude that they are very luminous objects. A comparison to two other luminous Of type systems studied in this series of papers, BD +40°4220 (Bohannan and Conti 1976) and HDE 228766 (Massey and Conti 1977) suggests the following similarities. The less-massive star has the more negative absorption line $\gamma$-velocity—suggesting a stronger stellar wind. Similarly, the emission lines are displaced redward with respect to the orbit, absorption-line velocity curve, but move in phase with it. A comparison of the actual numbers indicates a similarity between HD 166734 and HDE 228766 with the values for BD +40°4220 being more extreme. It is interesting that the mass ratios in the first two systems are near unity, whereas that of the latter is large, like that of WR binaries. We suggest that, like HDE 228766, HD 166734 is an evolved Of binary on its way to becoming a WR system, but not so far along as BD +40°4220.

Three other Of-type systems, in addition to those listed above, are known: Plaskett's star HD 47129 (Hutchings and Cowley 1976); 29 CMa (Struve *et al.* 1958; Hutchings 1977); and HD 152248 (Hill, Crawford, and Barnes 1974). These systems are all characterized by high luminosity for both components, similar masses, and probably considerable previous mass loss (aside from Plaskett's star). It is noteworthy that for all six systems, both components are well away from the zero-age main sequence and are evolving more or less in tandem. This is a consequence both of having similar initial masses when formed (according to the statistical arguments of Garmany 1979) and of mass loss (probably in both components) which tends to equalize the masses and lengthen the evolution time scales. A more thorough discussion of the evolution of O and Of type binaries will be carried out in a later paper of this series.

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