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HD 15558: AN EXTREMELY LUMINOUS O-TYPE BINARY STAR

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We present an orbital solution for the single-line binary HD 15558, an O5(f) star in the association IC 1805. The period is 440^d, the longest of any O-type spectroscopic binary, and $e = 0.54$. This star is one of the most luminous stars in the Galaxy and in the theoretical H-R diagram it lies near the track corresponding to stars with initial masses of 100 $\mathfrak{M}_\odot$.

Key words: binaries, spectroscopic—O-type stars

I. Introduction

HD 15558, BD $+60°502$, O5(f), is the most luminous star in the association IC 1805. According to Underhill (1967), Trumpler noted that it had a variable velocity with a range from -9 to -90 km s^{-1} and a period of 420 days, but no orbit has been published for this system. We have observed this star and determined its orbit in the course of a program begun by P. S. Conti to determine masses of O-type binaries (Bohannan and Conti 1976; Conti and Walborn 1976; Massey and Conti 1977; Morrison and Conti 1978, 1980; Conti et al. 1980). Most of the papers in this series deal with double-line binaries for which minimum masses can be determined. Although HD 15558 is a single-line binary, it is of interest for a number of reasons. Among all known O-type binary systems (see Garmany, Conti, and Massey 1980, Table 3) there are only three with spectral types O5 or earlier. HD 15558 is one of the most luminous O-type stars known, and radio observations with the VLA by Abbott, Bieging, and Churchwell (1981) have given a mass loss rate of 1.5×10^{-5} $\mathfrak{M}_\odot$ yr^{-1}. The masses of these early O-stars are very uncertain. More data are badly needed for comparison with the evolutionary tracks which have recently been computed using different assumptions about the mass-loss rate (de Loore 1980).

We present the orbit for HD 15558 based on 31 spectrograms taken mostly at Kitt Peak National Observatory (KPNO) and the Dominion Astrophysical Observatory (DAO). In section II we describe the observations, the measurement of the spectrograms, and their reductions. The determination of the orbit is discussed in section III and in section IV we discuss possible implications of the orbit with respect to stellar mass loss and evolution.

II. Observations and Reductions

Each of the authors began observing the star in the latter half of 1978. Fortuitously the star had just passed through velocity minimum and the steep rise of the velocity curve made it apparent that the star was a good binary candidate. Observations have continued until the present, using a variety of telescopes and instrumentation. The spectrographic data are summarized in Table I. The vast majority of the plates were taken with the KPNO coudé feed and S-20 "advanced Carnegie" design image tube; these spectrograms show very little distortion although the region covered is only λλ3750–3950, chosen so as to include the upper Balmer lines. A few later plates were obtained with the three-stage EMI tube at the Cassegrain focus of the DAO 1.8-m telescope. These spectrograms show considerably more distortion, but are still suitable for radial-velocity work. The remainder of the spectrograms were obtained without the use of an image tube. A few early DAO plates were kindly loaned to us by David Crampton; Peter Conti provided two plates taken at the coudé focus of the 5-m Hale telescope. All spectrograms were obtained with grating spectrographs: a few earlier prism spectrograms from the DAO plate vault were examined, but were not used in this analysis. All exposures were in the blue. An Fe-Ar hollow cathode or Fe arc was used for the comparison source.

The observations are given in Table II. The KPNO and Palomar plates were measured by C.D.G. on the JILA Grant machine in both a forward and reverse direction, and the results averaged line-by-line. These re-

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TABLE I

Spectrograph Data

J.D. (2,440,000+)	Telescope	Spectrograph	Emulsion	Dispersion (Å mm^{-1})
876.88-1572.97	DAO 1.8-m	Cassegrain	IIa-0	60
1586.90, 1588.04	Palomar 5-m	coudé	IIa-0	18
3771.84-3773.84; 3903.76	KPNO 0.9-m	coudé	IIIa-J,IIa-0	17
3841.87-3901.75; 3904.68-4202.90	KPNO 0.9-M	coudé	CIT+IIIa-J	10
4519.03,4586.74, 4620.67	DAO 1.8-m	Cassegrain	EMI+IIIa-J	30
4564.83, 4645.65	DAO 1.2-m	coudé	IIa-0	20
4576.80, 4606.70	DAO 1.8-m	Cassegrain	IIa-0,IIa-F	30

ductions were done by applying a cubic least-squares fit to the comparison lines, using the wavelengths provided by KPNO. The DAO plates were measured by P.M. on the Arcturus oscilliscope measuring engine in a single direction only, and these reductions were also done using a low-order polynomial fit. The comparison-line fit had a standard error for one observation of less than 2 km s^{-1} in all cases. The stellar lines measured included the Balmer lines from Hβ to H11; He II $\lambda\lambda$4200, 4541; He I $\lambda\lambda$3820, 4471 and occasionally the weak N III $\lambda\lambda$4540, 42 emission. (The latter were not included in the velocity averages.) The rest wavelengths of Conti, Leep, and Lorre (1977) were used for the stellar lines on the KPNO and Palomar plates, those of Moore (1945) were used for the DAO plates. Also shown in Table II are the number of lines included in the average and the mean errors. The typical mean error line-to-line of a single plate was 8 km s^{-1}. The interstellar H and K Ca II lines had a velocity of -16.0 ± 4.1 (1 σ) km s^{-1}.

III. Orbital Elements

We used the technique described by Lafler and Kinman (1965) to determine the period of the binary. The data in Table I were searched for all possible periods between 20 and 1000 days. A clear minimum in the residuals indicated a period of 440 days. A second period, with somewhat larger residuals, was found at 220 days. This second period was discarded as spurious after an examination of phase vs. velocity revealed four points, starting with JD2443900.64, which were nowhere near the rest of the observations. This spurious period arises from a combination of circumstances. The true period is close to a year, the eccentricity is large, and the observations are not spread uniformly over the period.

To compute the theoretical elements, we used a version of the differential correction program by Wolfe, Horak, and Storer (1967) which runs on the CDC 6400 at the University of Colorado. The analysis allowed the input period to vary. Table III gives the orbital elements and their mean errors as follows: the period in days (P), the radial velocity of the center of mass (γ), the semi-amplitude of the velocity variation (K), the eccentricity (e), the longitude of periastron (ω), the time of periastron (T), the semimajor axis of the orbit ($a \sin i$), and the mass functions [$f(m)$]. Figure 1 shows the observed velocities for HD 15558 plotted vs. the phases derived from the orbital elements in Table III, along with the computed velocity curve from these elements. We have included a velocity taken from Conti et al. (1977) for HD 15558: JD2440074.99, phase 0.62, -43.0 km s^{-1}. Although not used in the orbit computations, this earlier data point fits the computed orbit quite well.

IV. Discussion

Using a distance modulus of 11.8 for IC 1805 and classifying HD 15558 as O5(f), Conti and Burnichon (1975) derived $M_B = -10.85$ and $T_e = 46{,}800$ K for this star. Humphreys (1978) has listed it as one of the 15 most luminous stars in the Milky Way Galaxy. Of the 15 stars in her list, HD 15558 is the only known binary. Even if the secondary is contributing to the luminosity of the primary, it is doubtful if the effect could be more than about 0.3 magnitude since no evidence of the secondary is seen in the spectra. Therefore, HD 15558 remains as

TABLE II

Observations of HD 15558

J.D. (2,440,000+)	Phase*	Velocity (km s^{-1})	No. lines	M.E.
876.88	0.45	-39	6	7
887.04	0.47	-39	6	4
887.91	0.47	-47	6	4
1572.97	0.03	-85	4	7
1586.90	0.06	-82	9	5
1588.04	0.06	-86	8	5
3771.84	0.04	-89	9	7
3772.79	0.04	-90	11	5
3773.84	0.04	-94	12	4
3841.87	0.20	-58	4	10
3847.81	0.21	-51	4	6
3900.63	0.33	-43	6	9
3901.75	0.33	-56	5	9
3903.76	0.34	-49	10	5
3904.68	0.34	-47	7	8
4100.97	0.79	-20	8	3
4103.99	0.79	-11	8	7
4106.97	0.80	-10	8	15
4109.96	0.81	-14	8	9
4112.99	0.81	-13	7	7
4157.84	0.91	-28	8	7
4161.93	0.92	-18	7	8
4195.72	0.00	-48	6	9
4197.90	0.01	-65	7	9
4202.90	0.02	-62	6	8
4519.03	0.74	-37	5	5
4565.83	0.84	-12	7	3
4576.80	0.87	-7	7	6
4586.74	0.89	-25	5	11
4606.70	0.94	-34	5	7
4620.67	0.97	-52	2	6
4645.65	0.03	-77	8	3

*Based on T = JD 2440681.1, P = 440^{d}.

one of the most luminous stars in our Galaxy, and lies in a very interesting part of the H-R diagram. According to the evolutionary tracks of Chiosi, Nasi, and Sreenivasan (1978) it lies in the vicinity of the initial 100 $\mathfrak{M}_\odot$ track. If we adopt the radio mass-loss rate of 1×10^{-5} $\mathfrak{M}_\odot$ yr^{-1} (Abbott et al. 1981) and assume an age of 7×10^5 years (de Loore 1980), the present theoretical mass of the primary is 93 $\mathfrak{M}_\odot$. The mass function derived for HD 15558 is consistent with a very large range of primary masses, so little can be added to this. We can express the mass function as

$$f(\mathfrak{m}) = \frac{\mathfrak{m}_1 \sin^3 i}{Q(1+Q)^2} \quad ,$$

in which $Q = \mathfrak{m}_1/\mathfrak{m}_2$. Since we see no evidence for the secondary, let us assume it is at least 1 magnitude fainter than the primary, and therefore $Q > 2$. Furthermore, since $f(\mathfrak{m}) = 0.946$ it follows that $Q > 4$ only for $\mathfrak{m}_1 >$ 100 $\mathfrak{M}_\odot$ and large values of i, assuming that $\mathfrak{m}_1 > \mathfrak{m}_2$. Within the range $2 < Q < 4$, the mass function is consistent with a primary mass of 20 $\mathfrak{M}_\odot$ to 100 $\mathfrak{M}_\odot$ or greater. It would be very interesting if future observations could detect the secondary, especially if there was some indication of its spectral type.

TABLE III

ORBITAL ELEMENTS FOR HD 15558

$$P = 439^{d}.3 \pm 1^{d}.0$$
$$\gamma = -41.9 \pm 1.8 \text{ km s}^{-1}$$
$$K = 32.6 \pm 3.4 \text{ km s}^{-1}$$
$$e = 0.54 \pm 0.05$$
$$\omega = 116^\circ \pm 11^\circ$$
$$T = 2440681^{d} \pm 12^{d}$$
$$a \sin i = 1.7 \pm 0.2 \times 10^8 \text{ km}$$
$$f\mathfrak{m} = 0.946\ \mathfrak{M}_\odot$$

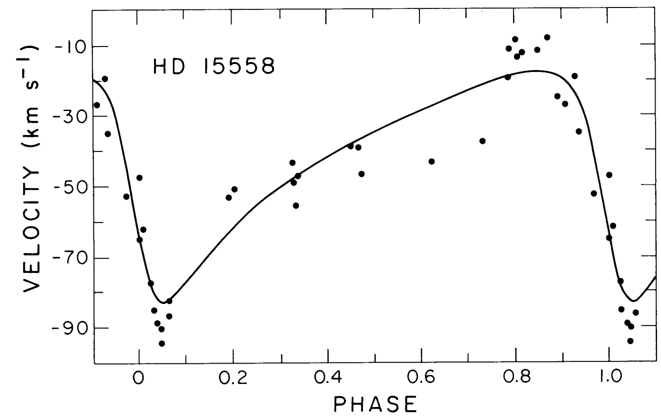

FIG. 1—Radial velocities of HD 15558 plotted as a function of phase. The solid curve represents theoretical velocities from the orbit solution. The orbital phase is zero at time JD2440681.1.

Although little can be said about the minimum masses of the two components, one can make some estimates of the separation of the two stars. If the sum of the minimum masses is 30 $\mathfrak{M}_\odot$ the separation is 3.5 AU or about 38 stellar radii, assuming the radius of the primary to be about 20 $R_\odot$. Thus interaction between the two components would be negligible, either for Roche-lobe overflow or stellar-wind mass loss. Nevertheless, it might be well to watch for changes in the stellar wind especially at perihelion.

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