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SPECTROSCOPIC OBSERVATIONS OF HD 153919 (2U 1700−37)

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ABSTRACT

High-dispersion spectrograms are used to derive radial velocities and magnetic-field intensities for HD 153919, the optical counterpart of 2U 1700−37, and to determine its spectroscopic properties. The primary component of this binary system is of type O6.5f, with unusually strong emission of He II, C III, and N III. The Zeeman measurements set an upper limit of about 4000 gauss to the strength of the observable magnetic field. If the mass of the primary is normal, the minimum mass of the secondary is 1.4 $\mathfrak{M}_{\odot}$.

Subject headings: binaries — magnetic stars — Of-type stars — stars, individual — X-ray sources

I. INTRODUCTION

The Of star HD 153919 has recently been proposed as the optical counterpart of the X-ray source 2U 1700−37. This identification has been supported by measurements which show that the radial velocity of HD 153919 (Thackeray and Walker 1973; van den Heuvel 1973) and the X-ray flux from 2U 1700−37 (Jones *et al.* 1973) both vary with the same period, 3.412 days. We have studied in detail the spectroscopic properties—line strengths, radial velocities, and magnetic field—of this interesting object.

II. OBSERVATIONS

Our observational material, obtained with the coudé spectrograph of the 224-cm telescope of the Mauna Kea Observatory, consists of 17 high-dispersion (6.8 Å mm^{-1}) spectrograms, centered at λ4400. All 17 spectrograms have been measured for radial velocity; 14 of the spectrograms, obtained with a Zeeman analyzer (Wolff and Bonsack 1972), were measured for magnetic field also. All the measurements were made with a Grant Instruments comparator with an oscilloscope display. It is common to find that comparators of this type introduce substantial systematic errors in measurements of broad lines. These errors can be minimized by making both "direct" (from shorter toward longer wavelengths with the emulsion up) and "reverse" (from longer toward shorter wavelengths with the emulsion down) measurements of the plates and averaging the results. This procedure changes the apparent direction of the Zeeman shift and should eliminate any bias toward positive or negative fields (Babcock 1962).

For HD 153919, we find that radial velocities derived from direct measurements are about 20 km s^{-1} more negative than those derived from reverse measurements. Furthermore, the bias in the magnetic field is substantial. Direct measurements yield positive fields, averaging +5200 gauss, for all 14 Zeeman spectrograms, whereas reverse measurements all give negative fields, averaging −4900 gauss. To check whether averaging together the direct and reverse measurements gives the correct field for broad lines, we have measured the three non-Zeeman spectrograms of HD 153919 as if they were Zeeman spectrograms, and we find the same bias as for actual Zeeman spectrograms. Averaging the direct and reverse measures gives fields close to zero, the correct result for non-Zeeman spectrograms.

III. RESULTS

a) *Description of the Spectrum*

We have made direct-intensity microphotometer tracings of spectrograms obtained on four consecutive nights (at phases 0.13, 0.41, 0.68, and 0.99), and table 1 gives average equivalent widths of selected lines. We find no persuasive evidence for variations in equivalent

TABLE 1
EQUIVALENT WIDTHS

LINE	EQUIVALENT WIDTHS (Å)	
	HD 153919	⟨O6.5f⟩
H + He II:		
3835...........	0.96	...
3889...........	0.95	...
4340...........	1.30	2.00
4861...........	0.58	...
He I:		
4026...........	0.55	0.56
4471...........	0.51	0.50
He II:		
3923...........	0.36	...
4200...........	0.52	0.56
4541...........	0.77	0.70
4686...........	2.50e	0.63e
N III:		
4640...........	1.80e	0.32e

width; the ratio of the largest to the smallest equivalent width obtained from the four measurements, never larger than 1.6, is typically about 1.3. In contrast, the X-ray source HZ Herculis varies between spectral types early B and late A (Crampton and Hutchings 1972), probably because the X-ray source heats one side of the primary. Smaller but definite changes in spectral type have also been observed in the optical candidate for Cygnus X-1 (Smith, Margon, and Conti 1973). Microphotometry of spectrograms that span several cycles of HD 153919 may reveal changes in line strengths or profiles (van den Heuvel 1973). Nevertheless, among the identified X-ray sources, HD 153919 has an unusually stable spectrum.

The observed value of the ratio of He I λ4471 to He II λ4541 (Conti and Alschuler 1971) corresponds to spectral type O6.5f, in good agreement with the type O7f assigned to HD 153919 by Thackeray (Crampton 1971). Table 1 lists, for comparison, estimates of the averages of the line strengths observed by Conti (1973*a*) for stars of type O6.5f. The absorption lines of both He I and He II in HD 153919 are normal, and we conclude that the secondary contributes little to the combined continuum. On the other hand, the equivalent widths of Hγ and the higher Balmer lines (Scholz 1972) are smaller than normal. The lines may be filled in by emission, but on our spectra only Hβ shows clear evidence of hydrogen emission that extends above the continuum. Since the absorption profile at Hγ is steeper on the red side than on the blue, this line may be filled in by emission, but other possible causes of the asymmetry are the blended line of He II and extension of the blue wing of the line by mass motions in the expanding atmosphere (see below). Redward of Hδ there is a complex emission feature, which rises above the continuum by about 10 percent, is 12–15 Å wide, and on all four spectrograms appears to have two maxima, one at about λ4106, the other at λ4116. In view of the width and structure of this feature and the absence of any visible emission at Hγ, it seems unlikely that the emission at Hδ can be due to hydrogen. Alternative identifications are N III λ4103 and Si IV λ4116, which are seen in emission in some Of stars (Hutchings 1968); but other lines which might also be expected to be in emission, such as N III λ4097 and Si IV λ4089, are in absorption.

The emission lines He II λ4686 and N III λλ4634 and 4640 are stronger than in most Of stars, being comparable in strength to the emission lines observed by Conti (1973*a*) in the extreme Of stars HD 108 and HD 152408. The blend C III λ4650 has a peak intensity about half that of N III λ4640 and therefore appears to be stronger than in any star examined by Conti. The unidentified lines at λλ4486, 4504 are not present, but their absence is not surprising, since Conti (1973*a*) finds these lines only between spectral types O7 and O9.5.

Comparison of HD 153919 with several stars of similar spectral type and known rotational velocity shows that $v \sin i = 140 \pm 25$ km s^{-1}. Since the radius of HD 153919 is at least 20 $R_\odot$ (see below), synchronism of rotation and revolution requires a rotational velocity greater than 300 km s^{-1}, much larger than our measured value. Synchronism should be established very quickly in a close binary, and it is not clear how so large a discrepancy could occur.

Conti and Alschuler (1971) have assigned an absolute magnitude of −6.3 to stars of type O6.5f. Using this value and the colors obtained by Crampton (1971) and assuming that the ratio of total to selective absorption is 3.0, we find that the distance to HD 153919 is about 1600 pc. This result is consistent with the value that would be derived from the interstellar K line (Münch 1968), which has an equivalent width of about 430 mÅ, and from the diffuse interstellar band λ4430 (Duke 1951), which has a central depth of about 9 percent. The radial velocity of the H and K lines is −13.2 km s^{-1}.

b) Search for a Magnetic Field

As an alternative to the hypothesis that the X-ray flux observed in some binaries is produced by the accretion of matter onto a collapsed object, Bahcall, Rosenbluth, and Kulsrud (1973) have proposed a model based on the twisting of magnetic field lines. This model requires fields on the order of 10^4 gauss at the surface of at least one member of the binary system. Observational confirmation that such large fields do exist in several X-ray binaries, including HD 153919, has been reported by Kemp and Wolstencroft (1973) and Kemp (1973), who have observed net circular polarization in Hβ. However, the derivation of a magnetic field for HD 153919 from the polarization in Hβ is uncertain. The profile of this line contains both an absorption component, probably due almost entirely to He II since its strength is comparable to that of He II λ4541, and a redward-displaced emission component. Conversion of circular polarization to magnetic field is possible only if the strength of the underlying absorption line, uncontaminated by emission, is known (e.g., Angel, McGraw, and Stockman 1973). Angel *et al.* (1973) have found no net circular polarization in the emission at Hα.

We have derived magnetic fields by averaging the direct and reverse measurements of eight absorption lines. The measured field strengths scatter equally on either side of zero: the largest value is −3500 gauss, all other values are less than 3000 gauss, and nine are less than 2000 gauss. Since the typical probable error of these values, estimated from the internal scatter alone, is ±2500 gauss, the measurements give no evidence that fields substantially in excess of 3500 gauss are present in HD 153919.

c) Radial-Velocity Variations

Radial velocities were determined for eight absorption lines and for the emission lines He II λ4686 and N III λλ4634, 4640. For the four absorption lines that

TABLE 2

RADIAL-VELOCITY DATA

$JD_{\odot}$ (2,441,000+)	Radial Velocity (km s^{-1})					
	Phase	H + He	Hγ + He	He I	He II	4686
769.09	0.60	−88	−129	−108	−59	+19
774.12	0.07	−67	−103	−111	−48	+23
788.94	0.42	−73	−97	−99	−37	+34
802.01	0.25	−74	−106	...	−61	+36
803.08	0.56	−95	−134	−112	−73	+15
809.06	0.31	−57	−85	−83	−36	+21
811.98	0.17	−67	−111	−91	−56	+32
820.91	0.79	−100	−138	−137	−86	−7
821.99	0.10	−56	−102	−105	−42	+14
822.07	0.13	−61	−78	−66	−38	+16
823.06	0.41	−66	−100	−90	−51	+29
823.97	0.68	−97	−134	−127	−73	−9
825.03	0.99	−81	−119	−105	...	+9
826.02	0.28	−55	−93	−83	−31	+12
843.97	0.55	−80	−125	...	−74	+15
844.92	0.82	−88	−122	−118	−73	+1
845.88	0.11	−63	−94	−84	−49	+28

are blends of H I and He II, we have arbitrarily adopted the laboratory wavelengths of the hydrogen lines. The resulting radial velocities are, therefore, the minimum values; if the lines were all He II, the radial velocities would be about 135 km s^{-1} more positive. For He I λλ4026, 4471, and He II λλ4200, 4541, 4686, we have adopted the wavelengths in the multiplet table.

The radial velocities are given according to element in table 2. The three blended lines at the positions of Hδ, H8, and H9 agree well with one another, and only an average radial velocity is given. The line at Hγ yields velocities that are decidedly more negative, and they are given separately. The velocities obtained for the two lines of He I also agree well with one another but are clearly more negative than the velocities derived from the two absorption lines of He II. Hutchings (1968) has obtained similar results for two other Of stars. He shows that their atmospheres are expanding and accelerating outward and that lines of He I and Hγ yield more negative velocities than do the higher Balmer and He II lines, because the latter are formed deeper in the atmosphere where velocities of expansion are lower.

Plots of the data show that all of the separate groups of lines, including the emission lines He II λ4686 and N III λλ4634, 4640 (not shown in the table), vary in the same period with the same amplitude. As is not the case for the optical candidate for Cyg X-1 (Brucato and Kristian 1973), the emission in HD 153919 appears to be closely associated with the primary component of the binary system. The radial-velocity curve derived by averaging the results for all the absorption lines in the table is plotted in figure 1 according to the X-ray elements

$$\text{JD (X-ray occultation)} = 2{,}441{,}453.14 + 3.412E\,, \quad (1)$$

derived by Jones *et al.* (1973). In agreement with observations reported by van den Heuvel (1973), the X-ray occultation occurs, as it should, at conjunction on the rising branch of the velocity curve. The velocity curve can be fairly well represented by a sine curve with an amplitude of 23 ± 4 km s^{-1}. Although the fit to this curve in figure 1 was made by eye, the representation of the data is satisfactory and indicates that the eccentricity of the orbit must be small. We therefore derive the value of the mass function

$$\frac{\mathfrak{M}_2^3 \sin^3 i}{(\mathfrak{M}_1 + \mathfrak{M}_2)^2} = (4 \pm 2) \times 10^{-3}\,\mathfrak{M}_{\odot}\,. \quad (2)$$

By comparing evolutionary tracks with the observed temperatures and luminosities of Of stars, Conti and Alschuler (1971) have shown that the minimum mass of an Of star is about 25 $\mathfrak{M}_{\odot}$. With this mass for the primary, the minimum mass for the secondary is 1.4 ± 0.3 $\mathfrak{M}_{\odot}$, and the secondary could be either a white

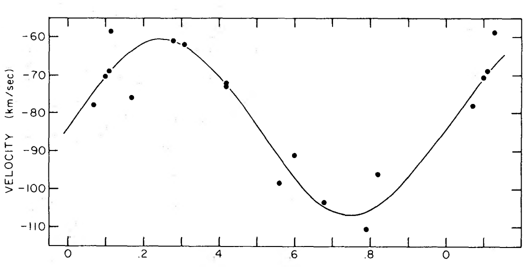

FIG. 1.—The radial-velocity variations of HD 153919. The solid curve is a sine curve of amplitude 23 km s^{-1}, which has been fitted to the data by eye. The absolute value of the γ-velocity is strongly affected by differential motions in the stellar atmosphere and is not equal to the velocity of the center of mass.

dwarf or a neutron star. The minimum mass of the secondary will exceed $2\,\mathfrak{M}_\odot$ if the mass of the Of star is greater than $40\,\mathfrak{M}_\odot$, a value that is certainly possible. However, the observations clearly do not compel us to conclude that the secondary is a black hole.

It is also possible to estimate whether the primary fills its Roche lobe. Since the duration of the X-ray eclipse is very long (Jones *et al.* 1973), the occultation must be nearly central and we take $\sin i = 1$. With $25\,\mathfrak{M}_\odot < \mathfrak{M}_1 < 40\,\mathfrak{M}_\odot$, the mass ratio $\mathfrak{M}_1/\mathfrak{M}_2$ is approximately 20. The size of the Roche lobe can then be estimated from the approximate interpolation formula (Paczyński 1971)

$$R_L/A = 0.38 + 0.2 \log (\mathfrak{M}_1/\mathfrak{M}_2) \,, \qquad (3)$$

where R_L is the average radius of the Roche lobe and A is the distance between the centers of the two stars. For $\mathfrak{M}_1/\mathfrak{M}_2 = 20$, $R_L/A = 0.64$. The size of the occulting disk responsible for the total portion of the eclipse is given by the standard formula

$$R_D{}^2/A^2 = \cos^2 i + \sin^2 b \sin^2 i \,, \qquad (3)$$

where b, the angle of occultation, is equal to 58° for HD 153919. For $\sin i = 1$, $R_D/A = 0.85$. These two results agree fairly well, and indeed Weedman and Hall (1972) have shown that it is not unreasonable for the occulting disk of the primary in such a system as this one to be slightly larger than the Roche lobe. Assuming circular orbits and $\mathfrak{M}_1/\mathfrak{M}_2 = 20 \pm 5$, we find that $R_L = 21 \pm 6\,R_\odot$ and $R_D = 30 \pm 9\,R_\odot$. We can estimate the photospheric radius of the primary directly from its luminosity and temperature. The spectral type is O6.5f, which corresponds to $M_V = -6.3$ (Conti and Alschuler 1971), $T_{\rm eff} \simeq 36{,}000°$ K (Conti 1973*b*), and $M_V - M_{\rm bol} = -3.2$ (Morton and Adams 1968). The calculated photospheric radius is then $19\,R_\odot$. For $i = 60°$, the radii of the Roche lobe, the occulting disk, and the photosphere of the primary are again comparable. It therefore appears that the primary of HD 153919 has filled its Roche surface and is transferring mass to the secondary. The fact that other known X-ray binaries behave similarly lends credence to the accretion model for X-ray sources.

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