1982Ap&SS..87..269S

SPECTROSCOPIC OBSERVATIONS OF DELTA ORIONIS

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(Received 20 April, 1982)

Abstract. The Hα profile in the spectrum of δ Orionis shows phase-dependent changes, with a period of variation equal to the orbital period of the binary system. The profile shape changes from a normal absorption profile at zero phase to a P Cygni-type at a later phase, to an absorption profile having emission at the centre of the profile, to a normal absorption profile at the end of the period. The spectra have been obtained at the Cassegrain focus of Kavalur Observatory telescopes (50 and 100 cm) at 17.2 Å mm^{-1} reciprocal dispersion and resolution 0.3 Å at λ 6562.817 Å. Assuming that the P Cygni profile is formed by a spherically-symmetrical region, the analysis gives a shell radius of 2.18 stellar radius and an electron density in the shell equal to 6.54×10^{-9} cm^{-3}, with the observed expansion velocity of 50 km/s^{-1}, a mass loss of 1.3×10^{-7} $M_\odot$ per year.

An analysis has been carried on the radial velocity data of earlier observers and the present radial velocity data. It is found that the orbital elements change. The presence of apsidal motion is confirmed by the increasing value of ω. The radial velocity of the centre of mass, γ, shows periodic variation. These observations confirm the presence of a third body. The values of K (mean amplitude), P (period), a sin i, and mass function $f(m)$, indicate a regular decrease, thereby confirming the mass transfer/mass loss from the system.

1. Introduction

The hot close binary δ Ori, O9.5 II (34 Ori, HR 1852, BD −0°983, HD 36486, ADS4134A) continues to be an important object for studying O-star atmosphere and envelope processes, stellar parameters, and stellar evolution. Rocket observations of ultraviolet spectra has been reported by Morton (1967), for UV spectrograms have been obtained by Morgan *et al.* (1975) and the normal region of the spectrum has been discussed by Conti (1974), Conti and Leep (1974). Morton (1967) observed P Cygni-type profiles for all the strong lines, and estimated the total mass loss at about 10^{-6} $M_\odot$ yr^{-1}. Conti (1974), and Conti and Leep (1974) noticed only slight distortion of absorption-line profile at Hα at red wing and no emission. Conti and Leep (1974), have also observed, the Hα line to be weak without any indication of wind velocity. The C IV and S IV lines show wind velocities of about 1400 km s^{-1} (Morton, 1967). This is clear that δ Orionis has extended expanding envelope. The spectroscopic orbits have been derived by Hartmann (1904), Jordan (1914), Curtiss (1914), Hnatek (1920), Luyten *et al.* (1939), Pismis *et al.* (1950), Miczaika (1951), Natarajan *et al.* (1971). It has a period of 5.732357 days, and the presence of apsidal motion has been confirmed.

2. Observations

The observations were taken from 19 February 81 to 26 February 81, 3 April 81 to 8 April 81 using a 50 cm reflecting telescope and 13 October 81 to 15 October 81, 10 November 81 to 11 November 81; and 8 December 81 to 11 December 81 us-

Astrophysics and Space Science **87** (1982) 269–277. 0004–640X/82/0872–0269\$01.35.

ing a 1 m reflecting telescope of Kavalur Observatory, on 09802 Kodak plates, at Cassegrain focus, at a reciprocal dispersion of 17.2 Å mm^{-1} at λ 6562.817. Out of these a total set of 11 calibrated spectra, widened 800 mm on the plate, have been used for profile variation study. For radial velocity measurements, 23 spectra have been used.

The spectra were traced on a Carl Zeiss microdensitometer at a dispersion of 0.3 Å and digitized manually. These density tracings were converted into normalized spectral intensity versus wavelength (I/I_{cont}, $I_{\mathrm{intensity}}$) with the help of intensity calibration plates recorded on a Hilgher Quartz prism spectrograph, with a rotating step sector. The position of Hα λ 6562.817 Å on each density tracing were determined by using comparison spectrum of hollow cathode neon tube λ 6532.8824 and λ 6598.9528 Å as defined by their centroid, and by C II lines at 6578.1 and 6582.9 Å in the spectra of ζ Cas, γ Peg, β Ori taken with the same spectrograph. The wavelength scale was transformed into a star-consistent velocity scale by the Doppler transformation of the wavelength of Hα at λ 6562.817 Å. No correction is applied to the measured intensity distribution neither for the instrumental profile nor any other reasons.

The emission on 12 December 1981, UT 20:42 one can see visually on the plate. On 15 October 1981, UT 22:33 one plate was recorded on Kodak IIIF to check the reliability of the data. The emission at the centre of the absorption profile was present on three plates recorded on Kodak 09802 and one plate on Kodak IIIF.

3. Variability of the Hα Profiles

The Hα line profiles obtained from 11 calibrated spectra are shown in Figure 1. They are arranged according to the phase of the binary orbit. The phases were calculated from

$$T_0 = \mathrm{JD}\ 2428382.263 + 5^{\mathrm{d}}.732357$$

following Pismis *et al.* (1950). A summary of the results of the evaluation of these profiles is given in Table I. The first column gives the date of observation; the second column, the mean UT of observation; the third column, JD; the fourth column, phase; the fifth column, equivalent width W in Å (W_{ab} = absorption equivalent width, W_{em} = emission equivalent width); the sixth column, full widths at half intensity (FWHI); and the seventh column, peak heights or central depths in units of interpolated continuum.

It is evident from Figure 1, that the profile is a normal absorption profile at a phase near to zero. It starts from a normal absorption profile, then at the next phase changes to a P Cygni profile, then emission appears at the centre of the absorption core, this emission vanishes gradually, and after that, emission probably appears at the violet wing (not very clear), and in the last profile becomes a normal absorption profile. Thus, the profile has a period of variation equal to the orbital period of the binary system.

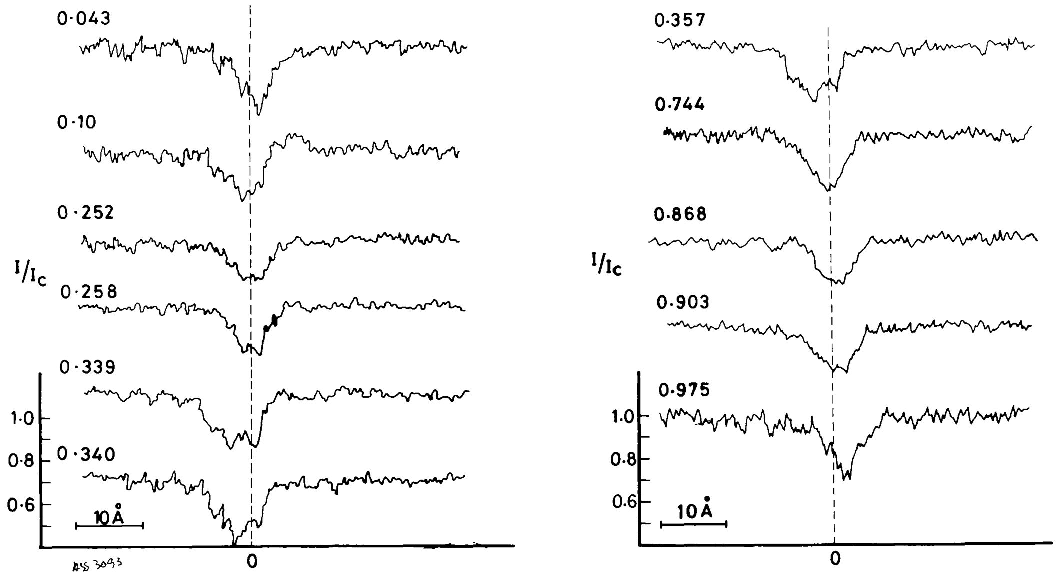

Fig. 1. Hα profile at different phase.

TABLE I

Measurements on Hα profile

Phase	Date	UT	JD 2444000+	W_{abs} (Å)	W_{em} (Å)	H (Å)	I/I_{cont}
0.043	11 Nov. 1981	20:57	920.357	1.823	0.000	5.000	0.68
0.100	10 Dec. 1981	20:42	949.351	1.117	0.390	8.667	0.80
0.252	11 Dec. 1981	17:23	950.220	1.267	0.020	7.000	0.82
0.258	11 Dec. 1981	18:13	950.255	1.276	0.018	6.333	0.78
0.339	15 Oct. 1981	21:45	893.394	2.040	0.013	12.333	0.75
0.340	15 Oct. 1981	21:63	893.401	2.083	0.000	7.333	0.71
0.351	15 Oct. 1981	23:15	893.464	1.783	0.000	6.666	0.74
0.744	8 Dec. 1981	19:40	947.308	1.726	0.000	6.666	0.73
0.868	10 Nov. 1981	20:57	919.357	1.250	0.000	6.333	0.80
0.903	9 Dec. 1981	17:27	948.219	1.533	0.000	7.000	0.80
0.975	13 Oct. 1981	19:40	891.308	1.833	0.000	6.333	0.70

4. Mass Loss Derived from P Cygni Profile

In Figure 2, we have shown a smoothed, normal absorption profile and a P Cygni profile taken from Figure 1. This P Cygni profile shows a wind velocity of 50 km s^{-1}, $W_{abs} = 1.117$ Å and $W_{em} = 0.390$ Å. The normal absorption profile

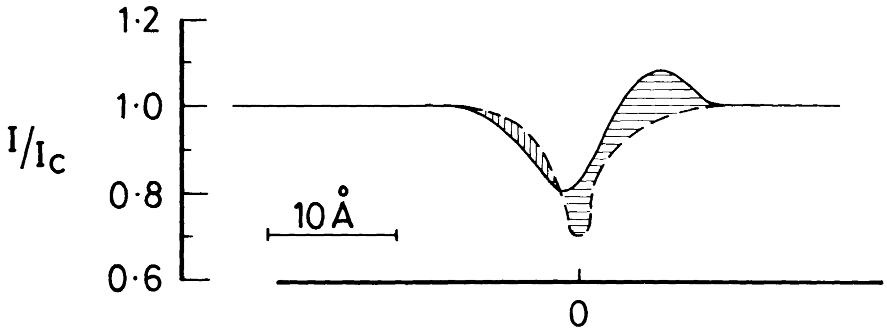

Fig. 2. P Cygni profile and normal absorption profile.

shows $W_{abs} = 1.823$ Å and $I/I_{cont} = 0.68$. Auer and Mihalas (1972), non-LTE profile for $H\alpha$ for 30 000 K and gravity 3.3 g, has an equivalent width 1.86 Å and $I/I_{cont} = 0.594$ and the LTE profile has an equivalent width 1.10 Å and $I/I_{cont} = 0.778$. Thus our observed profile agrees fairly well.

We assume that the P Cygni profile is formed by a spherically-symmetrical region, which may be called a shell, through which the expanding atmosphere flows. The dominant process determining the population densities of levels 2 and 3 of the hydrogen atoms in this region is photo-excitation directly from the ground-level by the continuous radiation of the star. Under these circumstances, the ratio of the population density of level 3 to level 2 is determined by the effective temperature of the star. For a given ratio of population densities of levels 3 and 2, the ratio of the emission from the shell to the absorption of the shell depends on the inner radius of the shell. A comparison of the ratio of the population densities with the ratio of the observed emission and absorption components gives the inner radius of the shell forming the profile. The average electron density of the shell is determined with a reasonable assumption about its thickness and from its ionization balance. If this star did not have an extended atmosphere forming the P Cygni-type profile, it would show a normal Hα absorption profile. The quivalent widths used in any interpretation must include the effect of this normal Hα absorption profile. In Figure 2, the two shaded areas, which are the differences between the observed P Cygni profile and the normal absorption profile, have been taken as the equivalent widths for emission and absorption of the extended atmosphere necessary to produce the observed P Cygni-type profile. The emission equivalent width, shaded horizontally, is 1.023 Å and the absorption equivalent width, shaded vertically, is 0.213 Å. Let us assume that the spherically-symmetrical region forming the Hα profile has an inner radius r and a radial thickness Δr and $\Delta r = r/3$; and r_0 as the radius of the star, $n_2\,\text{cm}^{-3}$ as the average density of hydrogen atoms in level 2, $n_3\,\text{cm}^{-3}$ as the average density of hydrogen atoms in level 3. Further, let us assume that the star emits as a black body at $T_{eff} = 31\,000$ K and that the radiation reaching the shell is sufficiently diluted, and $r_0 = 23\,R_\odot = 1.60 \times 10^{12}$ cm.

Following Hearn (1975) we arrive at the values of

$$r = 2.18\, r_0\,,$$

$$n_e = 1.242 \times 10^{10}\ \mathrm{cm}^{-3}\,,$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = 1.5759 \times 10^{19}\ \mathrm{g\,s}^{-1} = 2.49 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}\,.$$

Now taking into account departure from the black body radiation, one gets a mass loss rate of $1.314 \times 10^{-7}\ M_{\odot}$ per year and an electron density $6.54 \times 10^{9}\ \mathrm{cm}^{-3}$. This mass loss rate is less by a factor of 10 as compared to those of Morton (1967) but agrees well with that predicted by Lucy and Solomon (1967). Hearn (1975) in the case of ζ Orionis has concluded that the mechanism for mass loss from OB supergiants is a hot coronal wind and he did not agree that the mass loss is driven by radiation pressure (Lucy and Solomon, 1967). He has shown that the interpretation of the Hα profile and the observed expansion velocity give quantitative support to the coronal wind mechanism. But the same type of calculation does not hold good in the present case. Thus, probably it is not the coronal wind mechanism responsible for the mass loss in the case of δ Orionis. This present estimated value of mass loss favours for the mechanism driven by radiation pressure.

5. Radial Velocity Measurements and Analysis

In Table II we have presented, in order, date of observation, phase, JD, measured radial velocity, radial velocity calculated, and residual O–C from the elements finally adopted. Sterne's (1941) method and Schlesinger's (1908) iterative method have been used to arrive at the final elements. The same computer program (analysis) is applied to the data of Hartmann (1904), Jordan (1914), Luyten *et al.* (1939), Pismis *et al.* (1950), and Natarajan *et al.* (1971). The final orbital elements obtained in each case are shown in Table III. We have also determined the period in every case. The orbital elements for these data obtained earlier by the observers themselves or someone else, for comparison with our values are given in Table IV.

It is found that (Table III) the orbital elements change with epoch. There is evidence that an appreciable number of spectroscopic binaries change in their elements, other than apsidal motion from epoch to epoch. Change of K implies change in the total mass of the system. As is evident from Table III K is not constant, it has decreased in value, which confirms the indications of mass loss of the P Cygni profile.

There are several possible causes of these apparent changes. The first is instrumental and photographic effects on the spectrum. Good masses can only be obtained from spectrograms with dispersions of at least 20 Å mm^{-1}.

TABLE II

Radial velocity data

Date of observation	Phase	JD 2440000 +	Observed RV (km s^{-1})	Calculated RV (km s^{-1})	O.C. (km s^{-1})
11 Nov. 1981	0.043	4920.357	98.13	97.43	0.70
8 April 1981	0.063	4702.646	84.64	97.43	−12.79
8 April 1981	0.070	4702.687	84.64	97.43	−12.79
3 April 1981	0.205	4697.725	60.65	61.32	− 0.67
22 Feb. 1981	0.225	4657.721	60.20	48.60	11.61
11 Dec. 1981	0.252	4950.220	38.06	30.56	7.50
15 Oct. 1981	0.340	4893.401	−69.36	−40.05	−29.31
15 Oct. 1981	0.350	4893.464	−69.36	−47.98	−21.38
4 April 1981	0.380	4698.729	−46.98	−65.62	18.64
4 April 1981	0.387	4698.770	−46.94	−69.16	22.22
5 April 1981	0.556	4699.742	−61.60	−59.93	− 1.67
24 Feb. 1981	0.566	4659.676	−63.27	−55.72	− 7.55
6 April 1981	0.714	4700.646	7.28	8.61	− 1.33
19 Feb. 1981	0.726	4654.854	14.52	13.51	1.01
25 Feb. 1981	0.742	4660.683	21.30	20.44	0.86
8 Dec. 1981	0.744	4947.308	22.00	20.95	1.05
10 Nov. 1981	0.868	4919.357	61.68	65.11	− 3.43
7 April 1981	0.888	4701.646	71.40	71.10	0.31
7 April 1981	0.897	4701.700	71.40	73.86	− 2.46
9 Dec. 1981	0.903	4948.219	82.91	74.94	7.97
26 Feb. 1981	0.918	4661.690	82.91	78.86	4.05
20 Feb. 1981	0.925	4656.000	83.61	80.62	2.99
13 Oct. 1981	0.975	4891.308	98.13	90.47	7.66

Dispersion and resolution are the most obvious instrumental effects. Besides any possible direct effect of change in dispersion, possible systematic errors in the methods of measurement should also be considered.

The second possible cause to be considered is that the method of solution, introduce their own errors into the elements. To overcome this, we have analyzed all the previous data of different observers and our data, by the same computer program. The third possible cause of variation in orbital elements is the presence of an undetected third body in the system. This does not necessarily change only the systematic velocity. The combination of two periodic variations in the velocity of a star, if unrecognized, can change both the shape and the range of the observed velocity curve. Indeed when observations of a given system obtained at different epochs fail to agree, probably the most fruitful possibility to investigate is the existence of a third component. The orbital elements actually derived will be affected by the phases of the observations in both orbits, the number, distribution, and precision of the observations. In the present case, the value of ω increases at different epochs, and the radial velocity of the centre of mass, γ, shows periodic variation. These observations confirm the presence of a third body. In δ Orionis Heinz (1980) has

TABLE III

Orbital elements analysis by author

Observer (Observatory) Epoch	Hartmann (Potsdam) Feb. 1900 to March 1903	Jordan (Allegheny) Dec. 1908 to March 1912	Luyten *et al.* (Yerkes) Sept. 1935 to April 1938	Pismis *et al.* (Mcdonald) Nov. 1947 to Jan. 1948	Natarajan *et al.* (Kodaikanal) 1968–1970	Singh (Kavalur) Feb. 1981 to Dec.1981
No. of observations	42	36	140	48	49	23
ω(degrees)	0.02	9.33	44.49	72.89	104.32	139.07
γ(km s^{-1})	22.56	13.65	12.64	12.41	16.16	18.19
K(km s^{-1})	99.63	99.24	100.64	98.14	95.93	92.66
e	0.102	0.109	0.087	0.094	0.061	0.254
P(days)	5.733473	5.732869	5.732224	5.732761	5.732878	5.727731
$a \sin i$ km	0.7814184 E7	0.7776749 E7	0.7888799 E7	0.7702815 E7	0.7548654 E7	0.7057821 E7
$f(m)$ solar units	0.578383	0.570230	0.595369	0.554142	0.521511	0.427018
To Julian day	2416189.277	2419021.102	2428129.963	2432538.628	2440592.176	2444919.996
Comments	Analysis by Singh	Analysis by Singh	Analysis by Singh	Analysis by Singh	Analysis by Singh	Analysis by Singh

TABLE IV

Orbital elements analysis by previous authors

Observer	Hartmann	Jordan	Luyten *et al.*	Pismis *et al.*	Natarajan *et al.*
(Observatory)	(Potsdam)	(Allegheny)	(Yerkes)	(Mcdonald)	(Kodaikanal)
Epoch	1900–1903	1908–1912	1935–1938	1947–1948	1968–1970
No. of observations	42	36	140	48	49
ω(degrees)	4.9	20.4	38.0	70.8	106.96
γ(km s^{-1})	22.85	15.20	12.0	11.8	14.8
K(km s^{-1})	100.12	99.98	101.0	99.7	96.5
e	0.096	0.085	0.079	0.085	0.066
P(days)	5.7325	5.7325	5.731729	5.732357	5.732357
$a \sin i$ km	0.7850 E7	0.7850 E7	–	–	–
$f(m)$ solar units	0.589	0.588	–	–	–
To Julian day	2415793.756	2418981.295	2428382.26	2432509.466	2440437.41
Comments	Analysis by Jordan	Analysis by Jordan	Luyten *et al.* Analysis	Pismis *et al.* Analysis	Natarajan *et al.* Analysis

detected a visual companion which is not different in brightness from the binary system. This object at an angular separation of only 0.15″, must contribute to the light variation and possibly is the cause of orbital element variation.

The fourth possible cause is that at least one member of the system is intrinsically variable. The last possible cause of these anomalies is the action of proximity effects in a close pair such as gas streaming or reflections. The outer layers of stars in such systems are likely to be very unstable and probably real changes in the elements associated with gas-streaming, do take place. Probably this is obvious from the presence of the P Cygni profile. In the present case, the values of K, P, $a \sin i$ and $f(m)$, indicate a regular decrease, thereby confirming the mass transfer or mass loss from the system.

Now probably we can make the following statement about δ Orionis: δ Orionis is a mass-transfer binary and represents the higher mass counterpart to the familiar Algol systems. We believe that binary mass transfer is responsible for the circumstellar envelope.

Acknowledgement

The author is indebted to M. K. V. Bappu for his kind advice and discussion.

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