

THE PECULIAR O6f STAR HD 148937 AND THE SYMMETRICALLY SURROUNDING NEBULAE

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ABSTRACT

The ultraviolet continuum of the star is observed and, after standard reddening corrections are applied, it is found to be hotter than a model O5 V star. The Of star and its two companions are photometered around  $\lambda\lambda 4640, 4686, \text{ and } 4861 \text{ \AA}$ . The results confirm Westerlund's (1960) absolute visual magnitude of about -6 for the Of star and confirm his rejection of NGC 6164-5 as a planetary nebula. Peculiarities of the system of nebular shells around HD 148937, of which NGC 6164-5 are the innermost, are discussed with reference to radiofrequency data. A standard extrapolation from the optical flux density of NGC 6164-5 predicts a detectable radio source but it does not appear in the relevant surveys.

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HD 148937 is a peculiar O star and the brightest component of a triple-star system. It is unusually interesting because it is the nucleus of a series of symmetrically surrounding nebulae of radii 3', 13', and 44 - 64' as described by Westerlund (1960): His H $\alpha$  plate of the whole area is reproduced a second time in Johnson (1968). Following Westerlund (1960) we reject the classification of the innermost nebulae, NGC 6164-5, as a low-excitation planetary of about 6' diameter. A reproduction of a 74-inch plate of them is given by Westerlund and Henize (1967). Henize's (1959, 1967) planetary-nebula classification is followed by Perek and Kohoutek (1967).

Catchpole and Feast (1970) have confirmed Westerlund's (1960) conjecture that NGC 6164-5 would prove to be expanding from the central star. The radial velocities are  $\underline{v}(\text{NGC } 6164) = +21 \text{ km sec}^{-1}$  and  $\underline{v}(\text{NGC } 6165) = -43 \text{ km sec}^{-1}$ . Georgelin and Georgelin (1970) have also observed  $\underline{v}(\text{NGC } 6165) = -52.2 \text{ km sec}^{-1}$  in rough agreement. The projection factors on the line of sight are indeterminate.

We are indebted to Dr. W. M. Goss for permission to reproduce part of a red Palomar Schmidt plate which shows the area around NGC 6164-5 with an overlay map of 408 MHz contours in Figure 1. The three sources nearest NGC 6164-5 were also observed at 5000 MHz (Goss and Shaver 1970), and Wilson et al. (1970) included them in a survey of hydrogen 109- $\alpha$  line emission. Their radial velocities  $\underline{v}$ , reduced here from the published velocities with respect to the local standard of rest according to  $\underline{v} = \underline{v}(\text{LSR}) - 3.2 \text{ km sec}^{-1}$ , are: for source G 336.4-0.2  $\underline{v} = -71.7 \pm 1.8 \text{ km sec}^{-1}$ , for source G 336.4-0.3  $\underline{v} = -96.3 \pm 6.2 \text{ km sec}^{-1}$ , and for source G 336.5-0.2  $\underline{v} = -91.8 \pm 6.6 \text{ km sec}^{-1}$ . These velocities and the non-coincidence of any of the three sources with NGC 6164-5, despite proximity, make doubtful the identification of any radio source with NGC 6164-5.

But should NGC 6164-5 be observable in radiofrequencies? Red-passband surface-brightness measurements are given by Perek (1963) and by Westerlund and Henize (1967) independently except for the same zero point of scale. We reduce these data to integrated red magnitude  $7.5 \pm 0.4$  via measured dimensions of the nebulae. We attribute half of the red light to  $H\alpha$  because  $[N II] 6548-63$  is known to be about equal to  $H\alpha$  (Catchpole and Feast 1970). The Sun's integrated absolute red magnitude is 4.4, corresponding to a flux density of  $1.7 \times 10^{-11} \text{ W m}^{-2}$  in a similar red passband (Abell 1966), so that the flux density of  $H\alpha$  in NGC 6164-5 reduces to  $5 \times 10^{-13} \text{ W m}^{-2}$ . The relation of  $H\alpha$  flux density  $S_\alpha$  to 5000 MHz flux density  $S_\nu$  is  $S_\nu = 1.2 \times 10^{-14} S_\alpha \text{ sec}$  on the following assumptions: no interstellar extinction of the observed optical value, standard case B radiation, electron temperature  $10^4 \text{ }^\circ\text{K}$ , helium abundance 15 per cent, and small optical depth at 5000 MHz. We predict  $S_\nu = 6 \times 10^{-27} \text{ W m}^{-2}\text{Hz}^{-1} = 0.6 \text{ f.u.}$  for NGC 6164-5. However, if the interstellar extinction is 2.2 mag (Westerlund 1960), the predicted flux density becomes  $S_\nu = 4.5 \text{ f.u.}$  Several of the sources in the area of Figure 1 have  $S_\nu = 0.5 - 4.5 \text{ f.u.}$  and NGC 6164-5 should have been detectable. We must conclude that, although Goss and Shaver (1970) have mapped several other thermal and non-thermal radio sources within the largest shell of the system of nebulae around HD 148937, none of them is probably associated with these nebulae, and probably none of the radio sources has been optically detected.

Westerlund (1960) classified the brightest component of HD 148937 as O6fp. Smith and Aller (1969) report that class Ofp is almost unknown among strictly Population I stars, giving only HD 108 and HD 152408 as examples. HD 152408 (and another Of star, HD 151804) is in the cluster NGC 6231, and the cluster is in the large H II region RCW 113-116 (Rodgers et al. 1960) which shows some signs of peripheral structure. Hutchings (1968) observes

that the atmosphere of HD 152408 is accelerated away from the star to 600 km sec<sup>-1</sup>. Smith and Aller (1969) include HD 148937 with four other stars as nuclei of planetary nebulae, but according to our rejection of NGC 6164-5 as a planetary nebula HD 148937 is not such a nucleus. The only other very symmetrical nebula with an included Population I Of star, BD +60°2522, is NGC 7635. This may be a planetary but the Of star may then be accidentally associated (Johnson 1971a, 1971b).

HD 148937 has been observed photometrically with the 60-inch reflector at Cerro Tololo, using the narrow-band system and technique described by Johnson (1970). The system gives three indices in magnitudes related to the equivalent widths of spectral features at H $\beta$ , at He II 4686, and around N III-C III $\sim$ 4640, respectively denoted by  $\beta_1$ ,  $\gamma_2$ , and  $\gamma_1$ . They are independent of interstellar extinction. According to laboratory measurements of the filters the index values for continua without line features are  $\beta_1(0) = 2.531$  mag,  $\gamma_1(0) = 1.812$  mag, and  $\gamma_2(0) = 1.954$  mag. The stellar data were taken for about an hour each 1969 April 8 and April 11. They show small variability in each index within the range of  $\pm 0.01$  mag, scarcely above noise level. The mean values are  $\underline{m}(W) = -0.129$  mag,  $\beta_1 = 2.599$  mag,  $\gamma_1 = 1.812$  mag, and  $\gamma_2 = 1.911$  mag, where  $\Delta \underline{m}(W) = \underline{m}(\text{HD } 148937) - \underline{m}(\text{HD } 148974)$ . HD 148974 is a nearby comparison star of spectral type A5. The magnitudes  $\underline{m}(W)$  are from the wider (W) passband of equivalent width 179 Å around H $\beta$ .  $\Delta \underline{m}(W)$  also remains constant within a range of about  $\pm 0.01$  mag. The results show that net H $\beta$  is slightly in absorption, that no net deviation is present around  $\lambda$  4640, and that He II 4686 is in emission. These results agree with Westerlund's (1960) spectrographic study, noting that he found N III 4641 and C III (?) 4651 only sometimes in emission, along with great variability in the radial velocities. Westerlund's (1960) suspicion of UBV variability is confirmed by comparison of his  $V = 6.81 \pm 0.03$  mag,  $B-V = +0.42 \pm 0.03$  mag, and  $U-B =$

$-0.65 \pm 0.03$  mag, with Whiteoak's (1963)  $V = 6.71 \pm 0.01$  mag,  $B-V = +0.34 \pm 0.01$  mag, and  $U-B = -0.66 \pm 0.02$  mag (all errors rms).

Components B and C of HD 148937 also were observed photometrically at Cerro Tololo on April 11. According to Jeffers et al. (1963) the component separations AB and AC are  $2''.9$  and  $36''$ , respectively, and the magnitudes of A, B, and C are 6.8, 12.6, and 13.2, respectively. The observations were made with a diaphragm of  $7''$  diameter and a seeing disk of  $1''.5$ . The scattered light of A in the diaphragm setting for B was troublesome, and "sky" background for B was estimated by pointing opposite of B from A and with A as far from the edge of the diaphragm as it was with B centered. The means and their ranges for B are  $\Delta m(W) = 5.10 \pm 0.01$  mag,  $\beta_1 = 2.62 \pm 0.09$  mag,  $Y_1 = 2.33 \pm 0.12$  mag, and  $Y_2 = 2.17 \pm 0.18$  mag. The only conclusion from these rough data is that the star B probably does not show the observed features in emission. The results for star C are  $\Delta m(W) = 6.51 \pm 0.01$  mag,  $\beta_1 = 2.98 \pm 0.09$  mag,  $Y_1 = 1.76 \pm 0.03$  mag, and  $Y_2 = 1.88 \pm 0.04$  mag. Although the error in  $\beta_1$  is unaccountably large, this value of the index is consistent with spectral type AO V for star C. The absolute magnitude of star A is then -6, about as bright as normal Of stars. It agrees with the absolute visual magnitude derived from UBV photometry of star A by Westerlund (1960), and supports rejection of it as the nucleus of a planetary nebula.

HD 148937 has been observed under the OAO-2/NASA guest-investigator program with the WEP stellar photometers described by Code et al. (1970). The star was acquired three times on two consecutive days, and two regions near the star were observed for sky-background data. Normally the  $6'$  nebula NGC 6164-5 would be included with the star in the  $10'$  focal-plane diaphragm, but the star was apparently close to the edge of the field of view of the photometers in all observations, and even outside it during some of the observation time. Some data were also lost in transmission to Goddard Space

Flight Center. The remaining apparently good data of the star + nebula are presented here. The mean difference between any two raw star + nebula - dark data per passband was 2 per cent, and the sky averaged 9 per cent of star + nebula' - dark data. We have not found evidence that any of the light is nebular rather than stellar. The magnitudes per wavelength interval  $m_\lambda$  provided by WEP are reduced to relative flux per frequency interval, corrected for interstellar reddening, presented in Table 1 in arbitrary flux units, and shown in Figure 2. The correction for interstellar reddening is estimated from an interpolation of the "average"  $E(\lambda - V)/E(B-V)$  curve of Bless and Savage (1972) with the excess  $E(B-V) = 0.74$  mag derived by Westerlund (1960). Figure 2 also gives for comparison two theoretical atmospheres by Hickok and Morton (1968) from the emergent monochromatic fluxes for blanketed models tabulated by Bradley and Morton (1969). The observed spectrophotometric gradient  $df_\lambda/d(1/\lambda)$  is about 27 per cent steeper than that of the model 05 V star in the range  $3 - 6 \mu^{-1}$ . Hickok and Morton (1968) match the 05 V type to an effective temperature of  $37450^\circ\text{K}$  and  $B-V = -0.32$  mag. The latter equals the unreddened index used by Westerlund (1960), but the effective temperature of HD 148937 may not really exceed  $37450^\circ\text{K}$  if the ultraviolet reddening is less than the "average" correction which was actually applied. We do not know how to choose between these possibilities.

The 05f star  $\zeta$  Pup is observed in some detail in the present range of ultraviolet. Morton, Jenkins, and Brooks (1969), and Stecher (1970), discovered P Cyg profiles in several of its resonance lines including C IV 1548-50. This doublet falls in the S4F1 passband of WEP but it does not appear to perturb the continuum of HD 148937. There is no evidence of any other UV-line emissions or absorptions in HD 148937, but they would have to major in order to be significant in the rather broad passbands of the WEP photometers.

We conclude from these diverse results that all of the peculiarities point to current and past instability of a massive, very hot star, with non-uniform mass loss of visible ejecta over a period of several tens of thousands of years into a total volume of the order of  $10^5 \text{ pc}^3$ .

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#### REFERENCES

- Abell, G. O. 1966, Ap.J., 144, 259.
- Bless, R. C., and Savage, B. D. 1972, Ap.J., 171, 293.
- Bradley, P. T., and Morton, D. C. 1969, Ap.J., 156, 687.
- Catchpole, R. M., and Feast, M. W. 1970, Observatory, 90, 136.
- Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F. 1970, Ap.J., 161, 377.
- Georgelin, Y. P., and Georgelin, Y. M. 1970, Astron. and Astrophys., 6, 349.
- Goss, W. M., and Shaver, P. A. 1970, Australian J. Phys. Astrophys. Suppl., No. 14.
- Henize, K. G. 1959, A.J., 64, 51.
- 1967, Ap.J. Suppl., 14, 125.
- Hickok, F. R., and Morton, D. C. 1968, Ap.J., 152, 203.
- Hutchings, J. B. 1967, M.N.R.A.S., 141, 219.
- Jeffers, H. M., van den Bos, W. H., and Greeby, F. M. 1963, Index Catalogue of Visual Double Stars, 1961.0 = Pubs. Lick Obs., 21.

- Johnson, H. M. 1968, in Nebulae and Interstellar Matter, ed. B. M. Middlehurst and L. H. Aller (Chicago: The University of Chicago Press), 7, chapter 2, plate 6.
- , 1970, in Non-Solar Gamma and X-Ray Astronomy, ed. L. Gratton (Dordrecht-Holland: D. Reidel & Co.), p. 151.
- , 1971a, Ap.J., 167, 491.
- , 1971b, in Seventeenth International Astrophysical Symposium at Liège, in press.
- Morton, D. C., Jenkins, E. B., and Brooks, N. H. 1969, Ap.J., 155, 875.
- Perek, L. 1963, B.A.C., 14, 201.
- Perek, L., and Kohoutek, L. 1967, Catalogue of Galactic Planetary Nebulae (Prague: Academia).
- Smith, L. F., and Aller, L. H. 1969, Ap.J., 157, 1245.
- Stecher, T. P. 1970, Ap.J., 159, 543.
- Westerlund, B. 1960, Ark. f. Astron., 2, 467.
- Westerlund, B. E., and Henize, K. G. 1967, Ap.J. Suppl., 14, 154.
- Whiteoak, J. B. 1963, M.N.R.A.S., 125, 105
- Wilson, T. L., Mezger, P. G., Gardner, F. F., and Milne, D. K. 1970, Astron. and Astrophys., 6, 364.
- Rodgers, A. W., Campbell, C. T., and Whiteoak, J. B. 1960, M.N.R.A.S., 121, 103.



CAPTIONS

Figure 1.--H $\alpha$ -plate of NGC 6164-5, a "pair" of nebulae extending 3' northwest and 3' southeast of HD 148937 at 16<sup>h</sup> 30<sup>m</sup>.2, -48°00' (1950), or  $l = 336^{\circ}37$ ,  $b = -0^{\circ}22$ , with an overlay map of 408-MHz contours, provided by Dr. W. M. Goss. Note very weak arcs of nebulosity 13' southeast and 44' northeast of HD 148937.

Figure 2.--The observed relative flux per frequency interval of HD 148937 in the ultraviolet after correction for interstellar reddening (circles), and two model atmospheres by Hickok and Morton (1968).

TABLE 1

0A0-2 PHOTOMETRY OF HD 148937

WEP	Effective		Observed		Average	Relative
Photometer	FWHM	$\lambda$	$1/\lambda$	$m_\lambda$	$E(\lambda - V)$	Flux
Filter	(A)	(A)	( $\mu^{-1}$ )	(mag)	$\overline{E(B-V)}$	$f_v$
S1F3	860	4250	2.35	+0.220	1.14	1.91
1	520	3320	3.01	-0.043	1.85	2.40
4	410	2980	3.36	-0.150	2.31	2.88
S3F2	360	2460	4.07	+0.203	4.24	5.37
1	260	1910	5.23	-0.292	4.96	8.32
S4F1	270	1550	6.45	-1.260	4.48	9.55



