Mon. Not. R. astr. Soc. (1974) **166**, 491–497.

THE COOLEST WOLF–RAYET STARS

B. Louise Webster and I. S. Glass

(Received 1973 July 9)

SUMMARY

Four emission-line stars, M4–18, He 2-113, CPD $-56°$ 8032 and V348 Sgr, can be considered as a class, with low excitation surrounding nebulae, infra-red radiation from dust grains and characteristic spectra dominated by C II emission lines. They appear to form a cool extension to the carbon sequence of the Population II Wolf–Rayet stars. V348 Sgr is of particular interest as it has features in common with both the R Coronae Borealis stars and the planetary nebulae.

INTRODUCTION

Cowley & Hiltner (1969) have described the spectrum of CPD $-56°$ 8032 as unique. We wish to draw attention to certain other stars which resemble $-56°$ 8032 sufficiently closely that they may be considered together as a small class of objects whose evolutionary stage may perhaps be identified. The other members of this small class are Henize 2-113, M4–18, and possibly V348 Sgr.

CPD $-56°$ 8032 ($\alpha_{1950} = 17^{h}\ 04^{m}\cdot8$, $\delta_{1950} = -56°\ 51'$)

The blue spectrum of $-56°$ 8032 has been described by Cowley & Hiltner (1969). It contains a continuum, strong, slightly broadened C II emission lines and fainter emission lines from ions such as He I, C III, O II, O III, Si III and Si IV, many of the latter group having P Cygni profiles. The blue hydrogen emission lines are sharp and extremely weak and [O II] is present.

Our spectrographic material on this star (and the others) is described in Table I. The 1973 spectrogram agrees with the above description in the blue and gives information on the red spectrum in addition. Hα is quite strong relative to the continuum and the Hα/Hβ ratio is high. The [N II] λ 6583/Hα ratio is about 2 and the [O I] lines appear.

HE 2-113 = HENIZE (BE STARS) 1044 ($\alpha_{1950} = 14^{h}\ 56^{m}\cdot3$, $\delta_{1950} = -54°\ 06'$)

Henize (1967) found He 2-113 to be an emission-line star and his spectra have been studied by Carlson (1968). In our 1965 and 1973 spectrograms, the spectrum is dominated by strong emission-lines of H, C II and [N II] on an underlying continuum. Fainter emission lines of He I, C III, O II, [S II] and [O II] can be identified. Many of the permitted lines, He I and the higher Balmer lines in particular, have P Cygni profiles, the velocity difference 'emission–absorption' being about 200 km s^{-1}. The strong C II λ 4267 line, though, has no detectable absorption edge. Another fainter emission component shortward of the absorption can be seen in one or two He I lines. The description of the spectrum in 1962, given by Carlson (1968), basically agrees with ours.

TABLE I

Spectrographic material

Object	Local date	Observatory and telescope		Reciprocal dispersion (Å mm^{-1})	Spectral region (Å)	Detector	Remarks
M4–18	27/28.9.71	Isaac Newton	98″	210 I	3700–5900	Spectracon (S 11 cathode)	Electronic drift
He 2-113	13/14.5.65	Mt Stromlo	50″	94 (at Hγ)	3900–6800	103a-F	
	26/27.6.65	Mt Stromlo	74″	280 I	5800–6800	103a-F	
	28/29.7.65	Mt Stromlo	74″	140 II	4000–5100	103a-J	
	29/30.7.65	Mt Stromlo	74″	90 II	3700–4400	IIa-Obkd	
	5/6.2.73	Radcliffe	74″	155 I	3500–5900	Spectracon (S 11 cathode)	
−56° 8032	10/11.5.73	Radcliffe	74″	140 I	3500–7100	Carnegie I.T. (S 20 cathode)	

The radial velocities of the main emission-line components from the three best plates are -47 ± 5 km s^{-1} (H lines); -45 ± 17 km s^{-1} (C II λ 4267); -112 ± 6 km s^{-1} ([O II], [S II], [N II]) and -14 ± 28 km s^{-1} (He I). The C II λ 4267 line has a full width at half maximum of about 150 km s^{-1}, while the other strong emission components are unresolved. The parallel with the velocities in $-56°$ 8032 is quite striking, in particular, the relative C II, H and forbidden line velocities, although there are no H absorption edges in $-56°$ 8032.

Photoelectric photometry at Siding Spring Observatory in a narrow-band system (1965 March–June) implies that V (continuum) = 11·8 mag and that the spectral gradient is like that of a G star. Three measurements made over the three month interval show no variation greater than 0·06 mag. Direct red plates with the Radcliffe 74-in. telescope show that the star is unresolved, with no obvious surrounding nebulosity.

To produce a model for the emitting regions of this and the other stars is an interesting problem which will not be attempted here, even though it may bear on the interpretation of Wolf–Rayet (W–R) atmospheres (see below). Suffice it to say that in He 2-113 the observations indicate (1) an expanding, stratified atmosphere (from the line profiles), (2) that the hydrogen emission does not come entirely from either the forbidden-line region or from the C II region (line profile and velocity considerations) and (3) that the systemic velocity is probably that given by the forbidden lines, which originate away from the surface of the star and are unaffected by line absorption.

M4–18 = PK 146+7° 1 (α_{1950} = 04$^{\mathrm{h}}$ 21$^{\mathrm{m}}$·5, δ_{1950} = +60° 00′)

The only material available to us on M4–18 is the very low resolution spectrogram taken on the Isaac Newton Telescope. The strongest lines are again H and C II emission and [O II], which is stronger relative to the rest of the spectrum than in the other stars. The continuum is quite prominent and contains fainter emission lines (with some short wavelength absorption edges) from ions including He I, O II, C III and perhaps [S II].

V348 SGR (α_{1950} = 18$^{\mathrm{h}}$ 37$^{\mathrm{m}}$·4, δ_{1950} = −23° 03′)

Near maximum light, V348 Sgr is known to display just those spectroscopic features which are the common characteristics of the other three stars, that is, dominant C II emission lines and fainter emission lines of O II, N II, He I and Si III (Houziaux 1968). Absorption components are associated with many of the lines. Herbig's (1958) work has also revealed the presence of a small nebula, emitting hydrogen and low ionization forbidden-line radiation and most clearly visible when the star is at minimum. The infra-red measurements (next section) provide an additional link between the four stars. The physical conditions in and around V348 Sgr are clearly similar to those in He 2-113, M4–18 and $-56°$ 8032 and on this basis we can tentatively include it in the class.

V348 Sgr differs from the others in that its light varies dramatically and, spectroscopically, in that the P Cygni profiles are generally inverted (long-wavelength absorption). The two phenomena are presumably related, indicating a different and variable geometry for this star. The character of its light curve and its

TABLE II

Infra-red magnitudes

Object	Local date	Observatory and telescope		J	H	K	L
He 2-113	3/4.5.73	S.A.A.O.	40″	9·81 ± 0·24	8·87 ± 0·14	7·42 ± 0·09	4·62 ± 0·07
	26/27.5.73	Radcliffe	74″	9·75 ± 0·13	8·80 ± 0·10	7·37 ± 0·05	4·65 ± 0·06
−56° 8032	5/6.5.73	S.A.A.O.	40″	9·58 ± 0·13	8·66 ± 0·11	6·73 ± 0·06	3·56 ± 0·06
V348 Sgr	26/27.5.73	Radcliffe	74″	11·57 ± 0·19	9·40 ± 0·11	7·26 ± 0·08	4·96 ± 0·08

infra-red radiation led Feast & Glass (1973) to compare it with the R Coronae Borealis (RCB) stars, which makes its resemblance to the three stars of the present study of particular interest.

INFRA-RED RADIATION

A further property of interest comes from measurements in the infra-red. V348 Sgr has been shown by Feast & Glass (1973) to have strong infra-red emission from dust. We have examined $-56°$ 8032 and He 2-113 in J, H, K and L (1·25, 1·65, 2·2 and 3·5 microns) using the photometer described by Glass (1973) with the results given in Table 2. A new measurement of V348 Sgr is included for comparison. M4-18 is too far north for us to observe. The presence of strong, low temperature radiation, which can be most plausibly interpreted as being emitted by dust, is apparently a common characteristic of these stars.

The mean colours are:

	$V-K$	$J-H$	$H-K$	$K-L$
He 2-113	= 4·4,	= 0·95,	= 1·44,	= 2·76 mag
$-56°$ 8032	4·3	0·92	1·93	3·17
V348 Sgr	var	2·17	2·14	2·30

The visible colours and the $J-H$ indices indicate that the optical components contribute to the J magnitudes, at least. The $K-L$ indices (which are among the largest known) are relatively unaffected and yield temperatures for the dust emitting in this spectral region of around 600–800 K. The $V-K$ indices of our stars are comparable with those in Population I WC stars (Allen, Harvey & Swings 1972), but the dust temperatures are somewhat lower.

DISCUSSION

The data on the four stars is summarized in Table III. They are all at intermediate galactic latitudes, $4° < |b^{\rm II}| < 10°$, and, where it is known, have quite high radial velocities as judged from the forbidden lines. These velocities would put the objects well out of the galactic plane if due to galactic rotation. They therefore do not belong to Population I and probably are old disc population objects. V348 Sgr is apparently in the galactic bulge. The galactic position of V348 Sgr and the forbidden-line and/or interstellar K line velocities of He 2-113 and $-56°$ 8032 suggest that they are quite distant and have absolute magnitudes $M_{\rm V} \sim -3$ to -4.

TABLE III

Basic information

Object	$l^{\rm II}$	$b^{\rm II}$	Radial velocities (km s^{-1}) [ ]	H	C II	$\frac{\text{C II } \lambda 4267}{\text{H}\gamma}$ Peak intens.	Ref.
M4–18	146·80	+7·59	—	—	—	2·3	
He 2-113	321·04	+4·00	−112	−47	−45	~1	
$-56°$ 8032	332·92	−9·91	−117	−77	−68	⩾1	CH
V348 Sgr	11·19	−7·9	+212	+212	var	⩾1	H

References:
CH Cowley & Hiltner (1969)
H Herbig (1958)

Given also that they contain low density gas emitting forbidden lines of singly ionized atoms, a possible relationship with the planetary nebulae with W–R nuclei is obvious. This class of four stars forms a natural cool extension to the WC nuclei on several counts. (a) The ionization level in the stellar atmospheres is lower than in stars classified as WC9 as the C II/C III and He I/He II ratios are greater. (b) The C II lines are slightly broadened, but continue the correlation of cooler W–R stars having narrower lines. (c) No [O III] lines are seen in the shells surrounding our stars, so their far ultra-violet energy distribution is effectively cooler than that in the WC9 plus nebula objects, HD 167362, BD $+30°$ 3639 and NGC 40, in which the [O III] lines are seen. (d) Dust is not found in WN stars and increases as temperature decreases in WC stars (Allen *et al.* 1972). Furthermore, the planetary nebulae cited in (c) radiate by dust in the infra-red (Allen 1973; Willner, Becklin & Visvanathan 1972), and this dust is distributed throughout the system in $+30°$ 3639, at least. Our stars fit in well as they resemble WC9 stars with slightly cooler dust. Carlson (1968) also classifies He 2-113 as WC9+.

Following from this, we can take as a working model for these objects, one in which a star with a W–R-like atmosphere is expelling, or has expelled matter into a surrounding nebula. This is the model already proposed by Herbig (1958) for the particular case of V348 Sgr, in which the nebula is actually visible when the star is at minimum light. There is no evidence on whether, in the other three stars, the material actually escapes into interstellar space as it does in planetaries, or remains in the system as, for example, in some symbiotic stars. The relationship with the planetary nebulae that we are pointing out is one of comparative physical conditions, which may or may not indicate an adjacent evolutionary position.

A further interesting question is whether the central object is hydrogen deficient, having lost its hydrogen-rich envelope to the nebula. Cowley & Hiltner (1969) regard $-56°$ 8032 as hydrogen poor, while Herbig (1958) suggests that a normal H abundance and peculiar excitation conditions should be retained as an alternative for V348 Sgr. In He 2-113, the velocity of the H lines and their P Cygni profiles means that there is at least some hydrogen close to the star, rather than in the surroundings. For example, the forbidden lines would be >200 km s^{-1} wide if coming from the hydrogen region, whereas they are unresolved. Spectroscopically, then, $-56°$ 8032 and He 2-113 are essentially identical except for the H line strength, which suggests that excitation may not be solely responsible for the hydrogen line behaviour. Another relevant point comes from the fact that dust is apparently able to exist near these hot stars, although one might expect it to be destroyed by the various well-known destruction mechanisms. There are several instances of dust being present in stars with a higher C/H ratio than normal, e.g. the supposedly carbon-rich RV Tauri stars (Gehrz & Woolf 1970), RCB stars (Feast & Glass 1973), and a correlation between carbon enrichment and dust would explain the difference between the two W–R sequences found by Allen *et al.* (1972). This might be an indication that our stars are carbon enriched or hydrogen deficient. However, both these arguments about abundance are quite circumstantial and need independent confirmation.

To summarize, M4–18, He 2-113, CPD $-56°$ 8032 and V348 Sgr are all apparently disc objects and presumably in a late evolutionary stage. The first three form a natural extension of the planetary nebulae with WC nuclei to slightly cooler temperatures and their relatively narrow lines will be an advantage in understanding the physics of their, and perhaps other W–R atmospheres. Their greatest significance may be in their similarity in many respects to V348 Sgr. The erratic behaviour of this variable, and its resemblance to both the RCB stars and the planetary nebulae may mean that V348 Sgr has something important to tell us about mass loss during the late stages of stellar evolution.

ACKNOWLEDGMENTS

We have benefited from many interesting discussions with Dr M. W. Feast and from useful comments on the manuscript by Dr A. D. Thackeray. The Mount Stromlo and Siding Spring Observatories telescopes were used when one of us (B.L.W.) was at the Australian National University. Time on the Radcliffe and Isaac Newton telescopes was allocated by the Large Telescopes Users' Panel of the Science Research Council.

B. L. Webster:
Royal Greenwich Observatory, Hailsham, Sussex, England
and
Radcliffe Observatory, Pretoria, South Africa

I. S. Glass:
Royal Greenwich Observatory, Hailsham, Sussex, England
and
South African Astronomical Observatory, Cape, South Africa

REFERENCES

Allen, D. A., 1973. *Mon. Not. R. astr. Soc.*, **161**, 145.
Allen, D. A., Harvey, P. M. & Swings, J. P., 1972. *Astr. Astrophys.*, **20**, 333.
Carlson, E. D., 1968. Thesis (unpublished), Northwestern University.
Cowley, A. P. & Hiltner, W. A., 1969. *Astr. Astrophys.*, **3**, 372.
Feast, M. W. & Glass, I. S., 1973. *Mon. Not. R. astr. Soc.*, **161**, 293.
Gehrz, R. D. & Woolf, N. J., 1970. *Astrophys. J.*, **161**, L213.
Glass, I. S., 1973. *Mon. Not. R. astr. Soc.*, **164**, 155.
Henize, K. G., 1967. *Astrophys. J. Suppl.*, **14**, 125.
Herbig, G. H., 1958. *Astrophys. J.*, **127**, 312.
Houziaux, L., 1968. *Bull. astr. Inst. Czech.*, **19**, 265.
Willner, S. P., Becklin, E. E. & Visvanathan, N., 1972. *Astrophys. J.*, **175**, 699.