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THE EVOLUTION OF THE WOLF–RAYET FEATURES OF THE SLOW NOVA, RR TELESCOPII

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SUMMARY

Between 1951 and 1960, the spectrum of RR Telescopii contained broad emission bands similar to those in Wolf–Rayet stars, as well as a narrow nebular-line spectrum. As the nebular spectrum increased in ionization level, the equivalent Wolf–Rayet type of the bands varied from WN 6 to WN 3 or earlier and the bands became broader. The possible spectroscopic appearance of extremely high temperature Wolf–Rayet stars is described. It is suggested that the bands arose in the extended atmosphere of the nova remnant, which photoionized the outer nebula and supplied it with kinetic energy through mass loss. The remnant was rapidly contracting and increasing in temperature in the process of recovering from the nova outburst.

SPECTROSCOPIC BEHAVIOUR

The spectroscopic history of the RT Serpentis-type nova, RR Telescopii, has been observed from soon after outburst in 1945 to the present (see Thackeray 1969). The F supergiant spectrum at maximum was replaced in late 1949 by a rich emission-line spectrum which has increased steadily in ionization level with time. The line widths in this spectrum increased with ionization potential at any one epoch, but were always less than about 200 km s^{-1} and we shall refer to this emission-line system as the ‘nebular spectrum’. Between about 1951 and 1960, the spectrum also displayed much broader emission bands, resembling those in Wolf–Rayet (WR) stars, and the present communication describes the behaviour of these bands and their relation to the nebular spectrum.

The spectrograms that show the bands most clearly are listed in Table I. All were obtained by ADT with the two-prism spectrograph at the Cassegrain focus of the Radcliffe 74-in. (1·88-m) telescope and the dispersions at Hγ are indicated by the letters before the plate numbers: (a) 22·5, (b) 30, (c) 48 and (d) 86 Å mm^{-1}. Density tracings of the spectrograms have been made with a Joyce–Loebl microdensitometer and five representative tracings are shown in Fig. 1. The summary of the nebular spectrum given in Table I has been taken from Thackeray (1969) and from inspection of the tracings.

The column ‘strength’ of the bands, in Table I, refers to their visibility relative to the general spectrum. It is not possible to isolate a continuum which belongs just to the region giving rise to the bands. The ions represented in the band spectrum are summarized in the table. Those present at various epochs are He II 4686 and the Pickering series, N II 5680, N III 4634–41, N IV 3479–84, 4058, N V 4603–19 and C IV 5801–12, and also some severely blended bands. Those from 1951 to 1953 have already been described by Thackeray (1953, 1955), but are

TABLE I

			Wolf–Rayet bands			Nebular lines		
Plate	Year	Emulsion	Strength and width He II	Identification	Spectral type	Helium	Highest level Fe	Remarks
a 144	1951·5	103a-O	Medium 15 A	N III > N IV ≫ N V? He II 4686 ≲ N III	WN6·5	He II absent	[Fe III]	2
b 794	1952·4	103a-F	Medium 15 A	N III ≈ N IV ≫ N V? He II 4686 > N III N II, C IV	WN6	He II absent	[Fe III]	2
c 912[1]	1952·5	103a-O						
c 1342	1953·2	103a-E	Medium 22 A	N III ≈ N IV ≈ N V He II 4686 > N V C IV	WN5	He II absent	[Fe IV]	3, 4
c 1547[1]	1953·5	103a-O						
c 2428[1]	1955·4	103a-B	Medium 35 A	He II 4686 ≳ N V	WN3	He II 4686 < He I 4471	[Fe V]	5
c 2608[1]	1955·7	103a-B						
c 2675	1955·9	103a-F				4686 < 4471		
d 2822	1956·3	103a-F				4686 ≈ 4471	[Fe VI]	
d 3086	1956·8	103a-F3				4686 ≳ 4471		
c 3752[1]	1958·5	103a-F	Weak 42 A	He II 4686 > N V	WN?	4686 ≫ 4471	[Fe VII]	
c 4826	1960·4	103a-F	Very weak					

Notes to Table I

1. Shown in Fig. 1.
2. Thackeray (1953).
3. Thackeray (1955).
4. Smith (1955) classified the spectrum as WN 5+ in 1953–55.
5. The spectrum of HBV 475 in 1969 (Crampton *et al.* 1970) is similar to RR Tel in 1955–56.

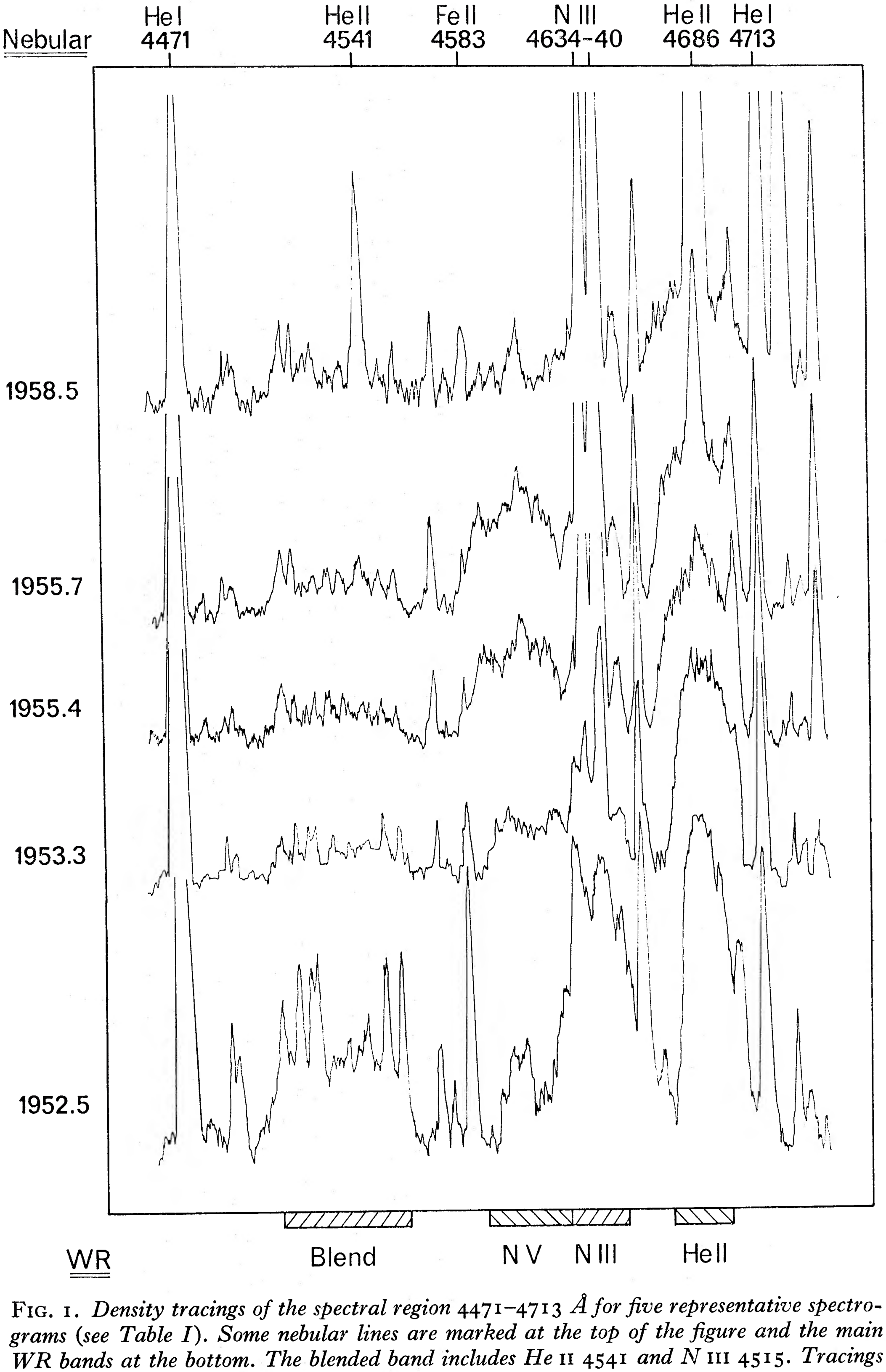

FIG. 1. *Density tracings of the spectral region* 4471–4713 Å *for five representative spectrograms (see Table I). Some nebular lines are marked at the top of the figure and the main WR bands at the bottom. The blended band includes He* II 4541 *and N* III 4515. *Tracings of strong nebular lines have been truncated—their strengths can be roughly estimated from their apparent widths.*

included here, with some revisions, for completeness.* Broad He I 4471 is possibly just present in plate a144, accompanying the strong nebular line.

The profiles of most of the bands are confused by blending, but He II 4686 is strong and affected only slightly by nebular lines. As can be seen in Fig. 1, its profile is round-topped with steep sides and the width increases steadily with time from about 15 Å in 1951–52 to over 40 Å in 1958. Values for the full width at half maximum of He II 4686 are included in Table I. Estimates can be made of the widths of some blended bands and it can be said that they do not all have the same width as He II 4686 at the same epoch. For example, in 1953 C IV is narrower than He II. Population I WR stars also show differences in line width between ions, probably because of stratification in their atmospheres (see Smith 1955).

An attempt has been made to classify the bands as if they arose in a normal WR atmosphere. This classification is hampered by superimposed strong nebular lines which tend to mask certain key bands like N III 4634–41. The classification criteria we have adopted are those given by Smith (1968) and we use the relative strengths of the bands N V 4603–19: N IV 4058: N III 4634–41. The He II 4686 band is also considered. After 1955, only the He II 4686 and N V bands were observable. In 1955–56, N V was sufficiently strong that N IV should probably have been seen if the type was WN 5 and we have used its absence to indicate an earlier type of about WN 3. In 1958–60, the bands were so weak that it was not possible to use the normal classification criteria. There was a change from 1955–56 in that the N V/He II ratio had decreased, reverting to about its 1953 value and since the He II band width was greater than before the temperature may have still been increasing. Generally, more reliance should be placed on our relative spectral types than on the actual subclasses.

After 1960, the bands were no longer visible above the nebular spectrum. The nebular He II/He I line ratio reached its maximum value and remained constant after this date and the Fe II and [Fe II] lines became strong again, although the level of ionization as judged from the [Fe VII] lines continued to rise. A deep, but low dispersion spectrogram obtained with a 'spectracon' image tube and the Radcliffe telescope showed no trace of the He II 4686 band in 1973. The physical reason for the increase in the He II 4686/N V band ratio between 1955 and 1958 is not clear, but if higher temperatures do suppress N V or intensify He II 4686, then it is tempting to suppose that the Population I WR stars with only He II in their spectra represent a hot extension to the class of WN stars.

A phenomenon that may be connected with the temporary presence of the WR bands is the emergence recently of a strong, unidentified red band at 6830 Å. A feature was visible as early as 1958 at 6823 Å and in 1973 the width of the main section of the band was 15 Å (660 km s^{-1}) with a long wavelength shoulder extending another 15 Å. A similar band, also double, is observed in the variable emission-line star, Henize 177 (Webster 1973a) and a strong unidentified line at about 6827 Å has been seen in some other novae, e.g. RS Oph and RT Ser (see Swings 1970). Whenever this feature has been seen, the level of ionization in the rest of the spectrum has been high which, together with the line width and the doublet structure, suggests that it comes from a permitted doublet transition in a fairly highly ionized ion. This lends support to the identification, proposed by

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* In the 1951 spectrum (Thackeray 1953, p. 230), the N designation has been erroneously given to the weak feature at 4649.4, attributed to the C III blend, whereas it should apply to N III 4639.9 (2N in 1951 increasing to 15NN in 1952).

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Dufay *et al.* (1964), with the Ca X doublet, 6832–53 Å, although, as they discuss, the relative intensities of the two lines may possibly be wrong. This ion has an ionization potential of 211 eV. Perhaps, therefore, an extremely high temperature Population I WR star would have a fairly featureless blue continuum and a prominent 6830 Å band. Most past spectroscopic surveys for WR stars would not have detected such a star.

DISCUSSION

It is not very easy to check whether RR Tel is the only nova in which WR bands behave in the way just described. Since its nebular lines are relatively narrow, the bands are easy to distinguish, whereas in faster novae all the spectral features are broad and would tend to mask bands from a central object. The 1969 spectrum of the variable, HBV 475 (Crampton *et al.* 1970), resembles RR Tel in 1955, but its behaviour with time is not yet known. The appearance of the bands in RR Tel is reminiscent of the well-known ‘nitrogen flaring’ in novae. In this, N III 4634–41 appears briefly as a diffuse, relatively bright emission band during the transition stage, while at the same time He II 4686 emission tends to be suppressed or to go into absorption. In RR Tel, the bands are a much more permanent feature of the spectrum and He II 4686 remains bright. It has been suggested that Bowen fluorescence is the driving mechanism in nitrogen flaring, whereas the wider variety of ions producing bands rule this out as the sole mechanism in RR Tel. (N V and other bands may be blended with flaring N III in some novae also, but this is speculative (Wright 1940)). Although there may be a connection between them, the two phenomena thus differ in what appear to be quite fundamental ways.

The widths, profiles and stable behaviour of the bands and the lack of broad forbidden lines indicate that the bands arise in a region with a density characteristic of a true WR star atmosphere, rather than of the nebular shell. It seems probable that in RR Tel we are seeing broad emission features arising in the extended atmosphere of the stellar remnant of the nova outburst. From Table I it is most striking that this nucleus has been increasing in temperature over the time interval, while the nebular ionization has also increased. It also seems likely that the nucleus was the major, if not the only source of ionization in the surrounding nebular shell, either through mechanical energy or through photoionization or both.

Some mechanical energy is almost certainly supplied to the nebula as the broadness of the bands ($\sim 2000 \text{ km s}^{-1}$) and the high velocity ($\sim 800 \text{ km s}^{-1}$) absorption components observed by Thackeray (1953) imply appreciable mass loss from the atmosphere. Conversely, Friedjung (1966) considered that a reasonable interpretation of the increase in line width with ionization potential in the nebular spectrum is that a central star is continuously ejecting material which is later decelerated in the shell. There is the possibility that this mass loss is sufficient to ionize the shell by collisions, but it is not obvious why this should lead to such a large rise in ionization level over the time interval. Although the width of the bands increased, the velocity of escape from the star did also, since the star was contracting (the luminosity as judged from the visible line radiation was decreasing slightly in spite of the temperature rise). Also, the nebular line widths of a given ion decreased slightly with time (Friedjung 1966) which argues against collisional ionization.

The ultraviolet flux from the central star should be sufficient alone to photoionize the surrounding shell and it is possible to investigate whether this is the ionization source by comparing the nebular level of ionization with the temperature of the star. According to ionization models of planetary nebulae computed by Harrington (1968), the He II 4686 line is detectable above stellar temperatures of about 70 000 K and by 90 000 K it is very strong in the nebula. Morton (1973) calculates that the effective temperature of a Population I WN 5 star is about 50 000 K and of a WN 6 star about 33 000 K. From Table I it can be seen that the spectral types and the corresponding He II strengths in RR Tel are in general agreement with a photoionization model. Another useful comparison would be with planetary nebulae with WN nuclei, but the only pure WN nucleus is that of the low excitation nebula, M1–67, which is WN 8 (Smith & Aller 1969). NGC 6543 displays N V and He II 4686 in its nucleus (Smith & Aller 1969) and has weak nebular He II, which is again consistent with RR Tel. In a study of the 1968 spectrum of RR Tel, Aller *et al.* (1973) concluded that photoionization was the exciting mechanism. It is interesting that if the photoionization model has been appropriate throughout the evolution of RR Tel, then in 1958–60, since the nebular [Ne V] and [Fe VII] lines were strong, we were seeing a Wolf–Rayet star with an effective temperature greater than 10^5 K!

The analogy with a planetary nebula with a rapidly changing WR nucleus is clearly an over-simplification. RR Tel is probably a binary system, as it was classified as a peculiar long period variable before outburst (Mayall 1949) and TiO bands have been seen on recent Radcliffe spectrograms (Webster 1973b). Also, the simultaneous presence of spectral lines of iron in all ionization stages between [Fe II] and [Fe VII] requires a more complicated model. However, in general terms it seems reasonable that a few years after outburst RR Tel contained a central star, with a WR-like atmosphere, which photoionized the surrounding gaseous shell and also gave it turbulent energy and/or outward velocity by means of a stellar wind. In just less than 10 yr, the central star decreased in radius and increased in temperature from about 30 000 K to greater than 10^5 K, with slowly decreasing luminosity, in the process of recovering from the nova outburst.

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