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The Continuum Energy Distribution of the Wolf-Rayet Star in $\gamma ^{2}$ Velorum

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The continuum energy distribution of the Wolf-Rayet star in γ^2 Velorum

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Near-ultraviolet S59 spectra of γ^2 Vel (WC8 + O9 I) and ζ Ori (O9.5 I) are studied. The luminosity ratio O/WC of the binary components of γ^2 Vel equals 1 at 2100 and 2500 Å. In the visible this ratio has been found to be 3.6 (Conti & Smith 1972). The empirical flux of the two components, expressed in monochromatic magnitudes, is compared with model energy distributions. An explanation for the high near-ultraviolet flux of the WC8 star is suggested in terms of a higher helium abundance.

1. Introduction

The continuum energy distribution of Wolf-Rayet stars and other stars with hot extended atmospheres is becoming a matter of increasing investigation. The observational study of Kuhi (1968) in the visible shows that the energy distribution of Wolf-Rayet stars does not resemble those of ordinary O- and B-stars. He finds a slight excess in the blue for the WN and a strong excess at the red, also for the WC. Modern space-astronomy techniques now allow to observe the ultraviolet and infrared radiation of the nearest Wolf-Rayet stars. In the meantime, work by several investigators constructing hot extended model atmospheres is underway. In order to make these models even more realistic one will in the future certainly try to leave the hydrostatic and radiative equilibrium assumptions.

The nearest Wolf-Rayet star γ^2 Velorum unfortunately is a spectrum binary of which the O9 I companion is 1.4 magnitudes brighter than the WC8 star in the visible according to Conti & Smith (1972). Our near-ultraviolet spectrophotometry together with the absolute small-band photometry of Stecher (1970) allows us to study the luminosity ratio of the two stars in γ^2 Vel at 2100 and 2500 Å. A discussion on the spectroscopy will be given in a later paper. The C IV λ = 2530 Å emission line has been discussed earlier (Van der Hucht & Lamers 1973, 1974) as well as the interstellar Mg I, Mg II and Fe II resonance lines (Grewing, Lamers, Walmsley & Wulf-Mathies 1972).

2. The observations

The Utrecht orbiting stellar spectrophotometer S59 (De Jager *et al.* 1974) observed the spectrum binary γ^2 Velorum (WC8 + O9 I) in May 1972 and May 1973 with 1.8 Å resolution in the wavelength regions 2060–2160 Å, 2490–2590 Å and 2770–2870 Å. The observations in 1972 and 1973 are performed at different orbital phases, 0.65 and 0.30 respectively. The radial velocity of the O star relative to the WC star differs 113 km s^{-1} between these two phases. Therefore we can easily distinguish the spectral features due to the O component, i.e. all the absorption lines except for some interstellar lines. An attempt is made to estimate the contribution of each of the two stars to the continuum flux in the observed wavelength ranges, by comparing some absorption lines with corresponding absorption lines in the S59 spectrum of ζ Ori (O9.5 I). Since all the absorption lines found in γ^2 Vel are superimposed on emission lines, it is not possible to measure equivalent widths and compare those. Therefore the spectrum of ζ Ori has been subtracted from that of γ^2 Vel with several assumed brightness ratios, in order to find the best eye-fit, without creating artificial emission lines in the resulting WC8 spectrum. This has been performed for both the 1972 and 1973 observations. In the 2100 Å region we looked especially to the absorption lines at 2096.5 and 2102.3 Å, in the 2500 Å region we used the lines at 2510.0 and 2516.2 Å. Identifications for these lines are listed in table 1. The 2800 Å region, being void of suitable stellar absorption lines, since the Mg II resonance lines are largely and the Mg I resonance line is completely interstellar, was disgarded.

Table 1. Identification of absorption lines used for determination of the luminosity ratio O/WC

measured wavelength in ζ Ori Å	identification			
	spectrum	laboratory wavelength Å	mult. no.	main or possible
2096.5	He II	2097.19	—	p
	Fe III	2097.48	67	m
	Fe III	2097.69	66	m
2102.3	Fe III	2100.96	129	p
	He II	2102.24	—	p
	Ti IV	2103.08	2	p
	Fe III	2103.80	66	m
2510.0	He II (triplet)	2511	—	m
	C II (doublet)	2512	14	p
	O IV	2507.73	—	p
	O IV	2509.19	—	p
	S III	2508.15	17	p
2516.2	Ti III	2516.01	7	p
	O IV	2517.20	—	p
	Si IV	2517.51	26	p

In this way we found for the 2100 Å region (figure 1), as well as for the 2500 Å region (figure 2), that each of the two components contributes 50 ± 5 % to the total observed *continuum* flux.

With Stecher's (1970) absolute flux measurement of γ^2 Vel, which is in the considered wavelength region in very nice agreement with the observation by S2/68 (Boksenberg *et al.* 1973) we have converted the instrumental count rate to photon flux, as shown at the right hand ordinate of figures 1 and 2. These empirical u.v. fluxes have been corrected for reddening with E(B-V) = 0.06 magnitudes using the average interstellar extinction curve adopted by Bless & Savage (1972). In order to compare with model atmospheres the fluxes have been converted to monochromatic magnitudes and normalized so that $m_\nu(1/\lambda = 1.82) = 0$ for both stars separately. For the normalization, the visual magnitudes of the two components have been taken from Conti & Smith (1972), who found the O star to be 1.4 magnitudes brighter than the WC star. With $A_v = 0.18$ we have m_v(WC8) = 3.3 and m_v(OgI) = 1.9. Further we used $I_{5480\,Å} = 3.64 \times 10^{-9} \times 10^{-0.4v}$ erg cm^{-2} s^{-1} Å^{-1} (Oke & Schild 1971). In figure 3 the normalized fluxes of the O9 I star and the WC8 star are shown (black dots) together with model fluxes from Mihalas (1972), Kurucz, Peytremann & Avrett (1972) and Cassinelli (1971). The models have been chosen with parameters as close as possible to the values $T_{\text{eff}} = 31\,000$ K and $\lg g \approx 3.2$, found for ζ Ori by Auer & Mihalas (1972).

Assuming that the O star does follow Cassinelli's model we can of course subtract the corresponding flux from Stecher's measurement for a longer wavelength range than the S59 comprises. The continuum on Stecher's spectral scans has been estimated between 1800 and 2800 Å in steps of 100 Å and reduced in the same way as described earlier. Shortward of 1800 Å the spectrum (with this resolution of 10 Å) is too crowded with lines to show the continuum.

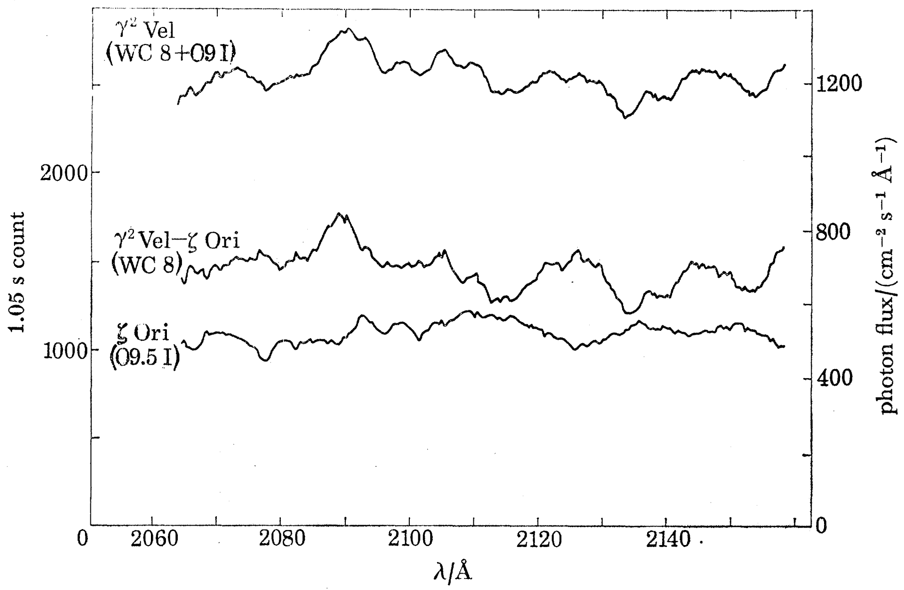

FIGURE 1. S59 2100 Å channel. Spectra of γ^2 Vel (WC8+O9 I), May 1972, an O9.5 I star (ζ Ori) and resulting WC8 star. The ordinates do not refer to the actual observation of ζ Ori but to the γ^2 Vel system.

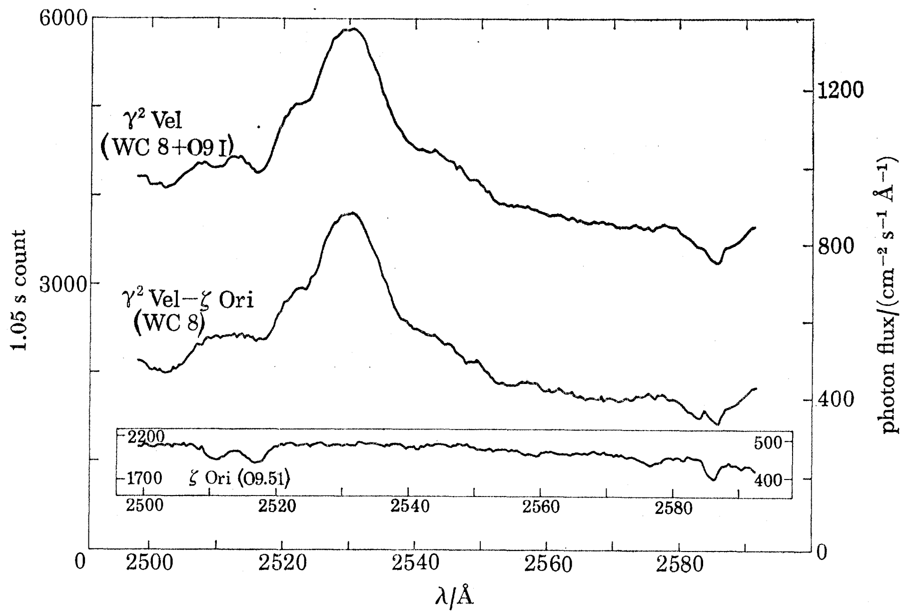

FIGURE 2. S59 2500 Å channel. Spectra of γ^2 Vel (WC8+O9 I), May 1972, an O9.5 I star (ζ Ori) and resulting WC8 star. The ordinates do not refer to the actual observation of ζ Ori but to the γ^2 Vel system. The absorption feature at 2586 Å is partly due to the interstellar Fe II line.

Longward of 2700 Å the spectrum drops off rapidly, possibly because of atmospheric extinction during re-entry of the rocket. The resulting WC8 flux is indicated in figure 3 with plus-signs. The corresponding luminosity ratio O/WC runs from 1.5 at 1800 Å via 1.0 at 2200 Å towards 2.5 at 2800 Å.

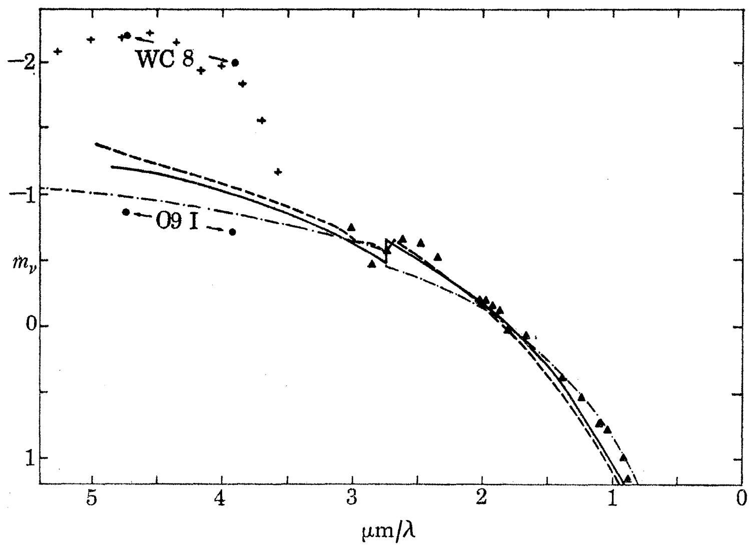

FIGURE 3. Empirical WC8 and O9 I monochromatic magnitudes (•) compared with model fluxes of several authors: —·—, Cassinelli $T(\frac{2}{3})$ = 37496 K, lg $g(\frac{2}{3})$ = 3.30, lg $g(0.001)$ = 2.72, ——, Mihalas (n.l.t.e./l. 30000 K, 3); - - -, Kurucz *et al.* (30000 K, 3.5); ▲, HD 192103 (WC8); +, WC8 flux from Stecher if O star follows Cassinelli.

3. Results and discussion

In their atmosphere models Kurucz *et al.* take u.v. line blanketing into account and assume, as Mihalas does, n.l.t.e. and plan parallel geometry. Cassinelli drops the plan parallel assumption but his model is in l.t.e. The geometrical extension of his model atmospheres effects the emergent flux in the sense that in the ultraviolet the continuum flux decreases with increasing geometrical extension. This is confirmed by Mihalas & Hummer (1974) for wavelengths 912 Å $< \lambda <$ 5695 Å. It is clear that the empirical O9 I flux can be explained in this way.

The empirical flux in the WC star is very high compared with the model fluxes, while in the visible the absolute photometry of an other WC8 star HD 192103, by Kuhi (1968), shows good agreement with Cassinelli's model flux. In the near-ultraviolet the WC8 flux is about one magnitude higher than can be accounted for by the hottest models published by the three authors, i.e. Mihalas 55000 K, Kurucz 50000 K and Cassinelli 94681 K. In order to account for this high WC8 flux one has to search for sources which increase the flux in the observed wavelength region. One source is the helium abundance in the Wolf-Rayet atmosphere. L. F. Smith (1968) has clearly pointed out that Wolf-Rayet stars may be helium stars. To investigate this, we have computed the model flux of Mihalas (T_{eff} = 30000 K, lg g = 3) model, with n.l.t.e. hydrogen and (for practical reasons) l.t.e. helium populations, adopting various helium abundances. One should realize that this is a rather crude method, because it ignores the fact that the atmospheric structure can be affected by a He/H ratio different from that for which the model atmosphere was computed, i.e. 0.1. Therefore our computations can only give a tentative picture, and have to be followed by the construction of real helium-rich n.l.t.e. extended hot model atmospheres. But the result we find is indeed that a higher helium abundance causes a

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higher flux, especially in the ultraviolet. For instance, a He/H ratio of 1.5 compared with a ratio of 0.1 gives at 2500 Å a normalized magnitude which is 0.2 magnitudes higher. This difference increases towards smaller wavelengths, namely 0.3 magnitudes at 2100 Å and about 0.4 magnitudes at 912 Å. In the visible the difference becomes negligible at longer wavelengths. This effect may, qualitatively, explain the observed WC8 flux in the near-ultraviolet. In the far ultraviolet (λ < 2000 Å) it is expected on this basis that in the γ^2 Vel case the WC8 star is brighter than the O9 I star.

Summarizing, we have come to the following conclusions:

(1) The luminosity ratio of the two stars in γ^2 Vel is 1 at 2100 and 2500 Å.

(2) The O star flux in the near-ultraviolet is in agreement with a geometrical extended model atmosphere.

(3) The high WC star flux in the near-ultraviolet may be due to high helium abundance in Wolf-Rayet atmospheres.

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