THE INFRARED RECOMBINATION-LINE SPECTRA OF WOLF-RAYET STARS

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Abstract. Effective recombination coefficients have recently been calculated for recombination lines of He I, He II and C IV (among other ions with up to three electrons) for densities and temperatures appropriate for Wolf-Rayet atmospheres. These have been applied to recently obtained infrared spectra of γ Vel in order to derive the He^{+}/He^{+2} and $C^{+4}/He^{+} + He^{+2}$ ratios.

1. INTRODUCTION

The determination of relative chemical abundances and ionization ratios in Wolf-Rayet stars is complicated by the breadth of the lines, which obscures the continuum level and produces severe blending problems, and by our ignorance of the atmospheric structure. The use of recombination lines involving highly-excited levels avoids some of these difficulties as the long-wavelength lines are likely to be optically-thin and the mechanism for their production is relatively simple. With recent developments in infrared spectroscopy, it is becoming possible to obtain observations with resolutions large enough to separate many blends. To utilize these observations, calculations of radiative recombination coefficients, appropriate for stellar densities, have been carried out.

2. RECOMBINATION COEFFICIENTS

The flux in an optically thin recombination line ($n\ell \to n'\ell'$), seen at earth after correction for interstellar absorption, is

$$I(n\ell\to n'\ell') = \frac{\alpha(n\ell\to n'\ell')h\nu}{4\pi d^2} \int_{V_i} dV\ N_e N_i \equiv \frac{\alpha h\nu}{4\pi d^2}\,[N_i] \qquad (1)$$

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where N_e and N_i are the densities of electrons and the recombining ion, $\alpha(n\ell \rightarrow n'\ell')$ is the effective recombination coefficient, V_i is the volume containing the recombining ion, and d is the distance. By defining

$$Q(n\ell \rightarrow n'\ell') = h\nu \ \alpha(n\ell \rightarrow n'\ell') \quad (2)$$

we obtain

$$I/Q = \frac{1}{4\pi d^2} [N_i] \quad . \quad (3)$$

Thus if the fluxes in several lines of the same ion are available, and the correct values of N_e and T_e are known, the ratios I/Q should all have the same value. Moreover, the ratios of I/Q for two different ions i and j give the ratio $[N_i]/[N_j]$. Thus if the electron density and volumes of each species are known, the relative specific abundances (N_i/N_j) can be estimated.

Brocklehurst (1970,1971,1972) computed effective recombination coefficients including collisional effects for H I, He I and He II. Hummer and Storey (1982) have generalized Brocklehurst's work to one, two and three electron systems of general ionic charge, have improved the treatment of collisions, and have carried the calculations to much higher densities. In order to interpret infrared spectra, they have tabulated the effective recombination coefficients for $n \leqslant 20$ and all ℓ-values. All optical-depth effects have been ignored except for the Case A/Case B assumptions of Baker and Menzel (1938). The high-density calculations show that, for the lowest several levels, the level populations for a given n are not proportional to $2\ell+1$. This conclusion is of particular relevance to attempts to model aspects of Wolf-Rayet atmospheres using escape-probability theory to reproduce the intensities of visual and ultraviolet lines, following the pioneering work of Castor and Van Blerkom (1970).

In principle, one could use line ratios of a given ion to determine the electron temperature T_e and density N_e, but because of the insensitivity of line ratios to T_e and N_e, we feel it is preferable to choose N_e and T_e from other considerations. The comparison of theoretical and observed line ratios can be used to detect blends and to insure that the theoretical assumptions are realistic. Spectral series containing several members are especially valuable in this regard.

3. FREE-FREE CORRECTIONS

Because the free-free opacity increases with wavelength, for the infrared lines it is essential to allow for the circumstance that recombination line emission is seen only from parts of the atmosphere which are optically thin in the free-free continuum. Between 1.6 and 10 μm an optically-thin free-free continuum flux has the form $F_\lambda \sim \lambda^{-1.85}$, The spectral index of the Wolf-Rayet star's free-free flux between 1.69 μm and the line wavelength was determined from

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$$\alpha_\lambda = -\ell n(F_\lambda/F_{1.69})/\ell n(\lambda/1.69) \quad . \tag{4}$$

The line intensity is then normalized by the index (α_λ-1.85), i.e. the corrected intensity is

$$I^{corr}(\lambda) = I(\lambda)\cdot(\lambda/1.69)^{\alpha_\lambda - 1.85} \quad . \tag{5}$$

For stars with a luminous companion, the uncertainties in this correction procedure are larger, as the contribution of the stellar continuum from the companion must first be subtracted. For γ Vel, this correction was made following the procedure described by Barlow, Smith and Willis (1981).

4. RELATIVE ABUNDANCES FOR γ Vel

For the WC 8 star γ Vel, we have used fluxes in the 1.4-4 μm and 8-13 μm regions obtained by Allen, Aitken and Roche (1982). As the free-free flux was found to be optically thin between 1.4 and 2.4 μm only the intensities for longer wavelengths were corrected as described above. In Table 1, both raw and corrected line intensities for He I, He II and C IV are given, along with Q-values for T_e = 30,000°K and $N_e = 10^{11}$. For each ion, in each wavelength region, the consistency of the I/Q values is satisfactory. The mean values of $[He^+]/[He^{+2}]$ are 3.8 and 6.2, respectively, for the 1.4-4 μm and 8-13 μm regions. This discrepancy is not yet understood, but may reflect a shift in the ionization in regions where the free-free opacity is less than unity. If this is true, the ionization of He decreases away from the star. However, regardless of the exact value of the He^+/He^{+2}, it seems clear that the number of He^+ ions is roughly five times the number of He^{+2} ions. Confining ourselves to the data in the 1.4-4 μm region, we find from Table 1 that $C^{+4}/(He^+ + He^{+2}) = 0.012$. This ratio is already much larger than the solar value of C/He; as the contribution of C^{+3} is likely to be significant, we can safely say that for γ Vel, C/He > 0.012.

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Table 1. He I, He II and C IV Recombination Lines in γ Vel

Ion	λ (μm)	10^{10} I	10^{10} I^{corr}	Q	I^{corr}/Q	$\langle I^{corr}/Q \rangle$
			1.4-4 μm			
He I	2.165	2.50	2.50	87.3(-29)*	2.8(17)	
	3.738	0.683	1.32	33.3	4.0	
	4.050	3.44	6.81	210.	3.2	3.6(17)
He II	1.476	7.77	7.77	7.69(-27)	1.0(17)	
	1.692	2.54	2.54	2.30	1.1	
	3.091	5.68	8.92	11.3	7.9(16)	0.9(17)
C IV	1.736	4.57	4.57	9.86(-26)	4.6(15)	
	2.427	2.78	2.78	6.45	4.3	
	3.281	1.12	1.89	2.77	6.8	5.3(15)
		10^{11} I	8-13 μm			
He I	11.30	1.45	0.88	9.21(-29)	9.6(17)	
	12.36	4.00	2.70	31.6	8.5	
	8.72	1.36	0.54	8.46	6.4	8.2(17)
He II	9.71	4.50	2.09	1.73(-27)	1.2(17)	
	13.12	1.52	1.13	0.77	1.5(17)	1.3(17)

*Number in parentheses indicates power of 10.

REFERENCES

Allen, D. A., Aitken, D. and Roche, P.: 1982, to be published.
Baker, J. G. and Menzel, D. H.: 1938, Astrophys. J. 88, pp. 52-64.
Barlow, M. J., Smith, L. J. and Willis, A. J.: 1981, Mon. Not. R. Astr. Soc. 196, pp. 101-110.
Brocklehurst, M.: 1970, Mon. Not. R. Astr. Soc. 148, pp. 417-434.
Brocklehurst, M.: 1971, Mon. Not. R. Astr. Soc. 153, pp. 471-490.
Brocklehurst, M.: 1972, Mon. Not. R. Astr. Soc. 157, pp. 211-227.
Castor, J. I. and Van Blerkom, D.: 1970, Astrophys. J. 161, pp. 485-502.
Hummer, D. G. and Storey, P. J.: 1982, to be published.

DISCUSSION

Nugis: Have you proposed the existence of a homogeneous ionization structure in a mass outflow envelope ? Most probably the state of ionization is lowering when one is moving away from the star's surface.

Barlow: In infrared spectra of Wolf-Rayet stars the emitting volume of a recombination line is determined by the free-free opacity of the wind. Since this changes with wavelength the emitting volume of the line also changes and so the ionization structure of the wind versus radius can in principle be followed by taking spectra in different IR wavelength regions.

Underhill: Surely what your procedures determine for each species is the product of the number density times volume. What assumption do you make about the volume occupied by each species in order to reach relative abundances ?

Williams: γ2 Velorum is a binary with a relatively bright companion; how did you correct the emission line strength ?

Barlow: The answer to Anne's question is covered in my reply to Nugis, and that from Williams is covered in the text of the paper.

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