HOT MANTLES, MODERATE PHOTOSPHERES FOR WOLF-RAYET STARS

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ABSTRACT

The amount of continuous energy from Wolf-Rayet stars and the shape of the continuous spectrum from the ultraviolet to the near infrared correspond to effective temperatures in the range 25000 to 30000 K. The value of log g is of the order of 4.0±0.5. Thus the photospheres of Wolf-Rayet stars correspond to those of moderately hot stars. The line spectra of Wolf-Rayet stars, however, indicate that electron temperatures greater than 30000 K occur in the outer atmospheres or mantles of these stars. Here outflow is important.

INTRODUCTION

To understand the meaning of WR-type spectra, it is necessary to think of the stellar atmosphere as being divided into two parts: a photosphere and a mantle. The photosphere can be modeled by traditional methods; it produces the continuous spectrum of the star. The mantle produces the emission-line spectrum and shortward displaced absorption troughs, as well as an infrared and radio-frequency spectrum. We are seeing the effects of the deposition of non-radiative energy and momentum in the mantle when we look at the line spectrum of a Wolf-Rayet star. The physical state of the mantle is primarily determined by the manner in which non-radiative energy and momentum are coupled to the gas which forms the outer part of the stellar atmosphere.

THE PHOTOSPHERES OF WOLF-RAYET STARS

That the effective temperatures of nine Wolf-Rayet stars fall in the range from 25000 to 30000 K has been shown previously (Underhill 1980, 1981). There is no way of determining log g in the photosphere from the observations of a Wolf-Rayet spectrum. However log g is probably of the order of 4.0±0.5 in the photosphere, according to the masses and radii of Wolf-Rayet stars. The effective temperatures of the Wolf-Rayet stars, found from integrated fluxes and angular diameters, may be confirmed by comparing the shape of the observed spectrum from 1200 to 5000 Å, corrected

C. W. H. de Loore and A. J. Willis (eds.), Wolf-Rayet Stars: Observations, Physics, Evolution, 47–51.

for interstellar extinction (Savage and Mathis 1979), with the shapes computed using model atmospheres. Both Willis and Wilson (1978) and Underhill (1981) have presented data showing that the continua of Wolf-Rayet stars have shapes which are consistent with effective temperatures in the range 25000 to 30000 K.

Another way of confirming that the effective temperatures of Wolf-Rayet stars found by Underhill are about correct is to look at the values of v_∞ for these stars. An empirical relation between v_∞ and log T_{eff} can be defined by means of data for O stars and B-type supergiants. The points for Wolf-Rayet stars lie close to this empirical relation. The upper limit for effective temperature suggested by the relation between v_∞ and log T_{eff} is 35000 K. It is valid to make this comparison only if the acceleration to v_∞ in the atmospheres of Wolf-Rayet stars is generated in about the same way as it is generated in the mantles of O stars and of B-type supergiants.

THE MANTLES OF WOLF-RAYET STARS

The line spectra of Wolf-Rayet stars correspond to electron temperatures which are higher than 30000 K. In the ultraviolet spectra of the 10 Wolf-Rayet stars which I have examined (HD 50896, 92740, 93131, 96548, 151932, 165763, 184738, 191765, 192103, and 192163), lines of C IV and Fe V appear. In the ultraviolet spectrum of HD 50896, the lines of Fe VI are strong, but the Si IV resonance lines are absent; Fe IV has marginal strength. In the spectra of the other nine Wolf-Rayet stars, the Si IV resonance lines are strong, and evidence for Fe IV is compelling; there is little, if any, evidence for Fe VI.

Rather similar profiles of the blended resonance lines of C IV appear in the ultraviolet spectra of all the Wolf-Rayet stars I have examined. In every case there is a strong absorption trough, and the emission component is strong; it is particularly strong for HD 165763. There is not much difference between the profiles of the C IV lines from the other nine Wolf-Rayet stars. The emission component always extends shortward of the undisplaced position of C IV 1548. The C IV profiles of Wolf-Rayet stars differ from those of O stars and B0 supergiants chiefly by having strong, broad emission components with peak intensities greater than 2. In Of stars and B0 supergiants, the peak intensity is usually less than 1.5, while the absorption trough is strong. The crossover point from absorption to emission occurs near 1548 Å for O stars and B0 supergiants.

The subordinate N IV line at 1718 Å can be detected in two WC stars (HD 165763 and 184738), and in the WN stars (HD 50896, 92740, 93131, 96548, 151932, 191765, and 192163). The N IV line is detected in all these stars in spite of severe blending with lines of Si IV and Fe IV. However, the absorption trough is not saturated like it is for the C IV resonance lines. The emission component for N IV 1718 is strong in most of the stars examine Even in the stars where N IV is weak (HD 184738 and HD 96548), the emission component is stronger, having intensity greater than 2, than is predicted, less than 2, for saturated resonance lines by the usual theories of lines formed in a wind (see, for instance, Castor and Lamers 1979, Hamann 1981).

The observed strengths of the emission lines of Wolf-Rayet stars are functions of the volume of gas in the mantle, the electron temperature, and the density pattern in the mantle. The strength of the absorption component reflects conditions in the part of the mantle which is projected against the disk of the star. All three factors may vary from star to star.

Intercomparison of the ions which produce the emission lines seen in the spectra of WN, WC, and Of stars, and of the strengths of the emission lines seen suggests that the electron temperatures are higher in the WN and Of mantles than they are in the WC mantles. However, there appear to be parcels of very hot gas in the mantles of WC stars, because some WC stars are known to show O VI lines in emission. The WC spectra contain many lines, most of them from C III. These spectra give the impression that they come from gas at a higher density than is present in the mantles of WN or Of stars.

To obtain the strong emission lines of Wolf-Rayet spectra, one must make a model mantle in which a large amount of hot gas is held close to the photosphere. Isolated emission lines in Wolf-Rayet spectra are observed to be truncated on their longward side, which results in a small negative displacement of the emission lines. This observation suggests that the occultation of the mantle by the body of the star is significant for affecting the profiles of the emission lines. It seems that most of the hot emitting gas is rather close to the photosphere.

A wind does flow from each Wolf-Rayet star. This moving material attains quite high velocities. It does not appear to be so dense as the part of the mantle which gives the emission lines. On the whole, the winds of Wolf-Rayet stars produce somewhat stronger absorption troughs than do the winds of Of stars and B0 supergiants, particularly for the subordinate lines.

CONCLUSIONS

In summary, to interpret the spectra of Wolf-Rayet and Of stars, one should use a model consisting of a traditional photosphere at moderate temperature surrounded by an inhomogeneous, hot mantle. The higher the temperature in the emitting region, the lower the density, on the whole. The densest part of the mantle seems to be confined close to the photosphere. The amount of the material in the mantle of a Wolf-Rayet star varies greatly from star to star; it appears to be larger than the amount of material in the mantle of an Of star or a B-type supergiant. Wolf-Rayet stars are surrounded by moderately cool, $T_e \approx 22000$ K, post-coronal regions which emit free-free radiation in the infrared and radio wavelength ranges. These regions may extend out to 40 or 50 stellar radii.

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DISCUSSION

Abbott: Given the extended nature of the WR envelopes - and in particular that the radius of optical depth unity is a strong function of wavelength - do you think it is meaningful to compare WR fluxes to plane-parallel, hydrostatic models ?

The correlation of v_∞ with T_{eff} may be misleading, because in a sample of mainly supergiant stars, both T_{eff} and gravity decrease together.

I am surprised that you think that doubly excited states are important in N V, as this is a lithium-like ion and the excitation energy is very high. Could you comment ?

Underhill: 1) The radius of a photosphere with T_{eff} near 30000K is not a sensitive function of wavelength. For plane parallel atmospheres and static spherical atmospheres, which are all that exist, $\Delta R/R$ varies with wavelength by very little, see the work of Mihalas and Hummer about 1974 and that of Gruschinske and Kudritzki 1979 in Astron.Astrophys. The variation is about the same for F_ν between 1300 and 7000Å in plane parallel leyers and spherical atmospheres. Thus planar atmospheres are adequate for interpreting the continuum. Only hydrostatic model atmospheres exist.

2) I presented an empirical relation between T_{eff} and v_∞ . It exists, although the scatter about it is large. I do not attempt to explain how it comes about.

3) The doubly excited states of N V lie only a bit over 100 eV from ground of N V. That is not an exhorbitant amount of energy once you realize that the electron temperature in at least parts of the mantles of WN stars may be of the order of 10^5 K.

Conti: The major spectroscopic difference between WN and WC stars in the UV in the line λ1909 C III. It is present in WC stars but not in WN stars.

Underhill: In WN spectra you see the intersystem line of N IV at λ1486 in place of the CIII intersystem line. My overall impression of WN and WC spectra is that WN spectra correspond to higher electron temperatures than do WC spectra.