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N. K. VAINU BAPPU

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N. K. VAINU BAPPU

Uttar Pradesh State Observatory, Naini Tal.

Introduction.

The Wolf-Rayet stars form a group of objects that have numerous peculiar features in their spectra. They are so named after their discoverers Wolf and Rayet of the Paris Observatory who first picked out three examples of such spectra around the middle of the last century. Later, during the century, numerous additional discoveries, by visual methods as well as by the newly developed technique of objective prism photography, increased the list considerably. We thus have available today a fairly complete survey beyond magnitude 11·0 both in our galaxy as well as the nearby Magellanic clouds. Such a survey indicates that these objects are rare among the different celestial species commonly found in the vicinity of the sun.

Spectral Characteristics

The spectra of the Wolf-Rayet stars are characterised by broad emission bands having halfwidths of 10Å or more. In some rare cases these emission bands are accompanied by violet absorption edges similar in nature to those found in the P Cygni stars. The investigations of Edlen[1], Miss Payne[2] and Beals[3,4] have greatly aided identification of most of the contributing elements to these spectra. The emission lines identified definitely are those of He I and He II, C II, C III and C IV, N II, N III, N IV, O III, O IV, O V and O VI, and Si II, Si III, Si IV. The spectra exhibit a wide range of excitation conditions in the atmosphere of the star.

If the large widths of the emission bands are interpreted as due to velocities of motion of the atoms in the stellar atmosphere, then we find that the postulated velocities are in the neighbourhood of 2000 kms/sec. or more. The first explanation for the large widths of the emission bands was given independently by Menzel and Beals. They assumed an expanding shell about a hot star wherein the emission mechanism is primarily that of ionization and recombination. Such a hypothesis seemed to explain several of the features of Wolf-Rayet spectra, like the flat-topped profiles mentioned by Beals, the violet

Its absence, therefore, becomes all the more conspicuous. The detection of weak N II in the carbon sequence and of carbon lines in the nitrogen sequence proves the non existence of a completely pure carbon or nitrogen sequence, although it is obvious that the intensities of the observed lines of carbon and nitrogen in both sequence do not suggest that the relative abundances, as are likely to be inferred from the line intensities of these elements, are similar to the values observed in normal stars.

Kinematical Features :

A necessary consequence of the simple expanding shell is the occurence of flat-topped profiles for the emission lines. The 5696 Å line in HD 192641 and 4058 Å line in HD 191765 of the nitrogen sequence were shown by Beals to possess such profiles and these seemed to indicate the success of the expanding shell model. On high dispersion plates such flat-topped profiles for the emission bands cannot be seen; on the other hand they show clearly that the final shape of the band is due to the blending of the individual components that constitute the "fine structure".

Wilson [7] was the first to question the validity of Beals expanding shell hypothesis since the "transit time effect" that he predicted on the basis of it cannot be detected in the binary system V 444 Cygni. The absence of the "transit time effect" and of flat-topped profiles for the emission lines cannot be taken, however, as definite proof of the failure of the expanding shell model. If a range in ejection velocities exists, the flat-topped profile will be defined by the lower limit of the velocities as has been shown by Menzel and the author[8]. If this value is essentially low we can hardly observe it.

In a study of the profiles of emission lines in V 444 Cygni, Munch[9] has shown that electron scattering increases the widths of the lines. While the contribution of electron scattering may not be such as to explain the entire widths of the emission bands, nevertheless it would constitute a sizeable factor.

Temperature :

Temperatures have been derived for many Wolf-Rayet stars on the basis of different postulates concerning the mechanism of emission line formation. Beals, assuming the Zanstra-Menzel mechanism of photoionization with subsequent recombination, derived from measures of the emission line intensities, temperatures of 90,000° for HD 192103, and 70,000° for HD 184738 (Campbell's hydrogen envelope star). Aller[10] has obtained excitation temperatures for HD 192103 which range from 28,000° to 75,000° depending on the kind of ion used for the analysis. Higher excitation potential lines like those of C IV are assumed to originate lower in the atmosphere than those of He I, indicating thereby a decrease of excitation with increasing distance from the centre. On the other hand Thomas[11] considered the case wherein microscopic motion alone in the form of $T_e > T_r$ (where T_e and T_r are the kinetic and radiation temperatures respectively) is sufficient for atmospheric support.

Consider the case of two emission lines that are the results of transition $n' \rightarrow n$ and $n'' \rightarrow n$. The excitation temperature is then given by :

$$T = \frac{(\nu_n' - \nu_n'')\frac{h}{k}}{ln\left(\frac{I_{n'n}}{I_{n''n}}\right) - ln\left(\frac{A_{n'n}\,\nu_n'\,\omega_n'}{A_{n''n}\,\nu_n''\,\omega_n''}\right) - ln\left(\frac{b_n'}{b_n''}\right)}$$

Here, T the excitation temperature can be identified with the kinetic temperature in the limiting case. $A_{n'n}$ is the Einstein coefficient for spontaneous transition $n' \rightarrow n$ and b_n', b_n'' are parameters that yield the ratio of the actual populations of the levels n' and n'' to the populations expected under conditions of thermodynamic equilibrium.

The theoretical studies of Thomas[12] and Chamberlain[13] have shown that for large values of n, $b_n \longrightarrow 1$. Hence if n' and n'' are both large b_n'/b_n'' should be nearly unity. Also b_n for any n at a particular value of T_e, decreases rapidly with large nuclear charge. If then, we consider line intensities of any ion having a larger nuclear charge than hydrogen and helium, we can assume with confidence that if n' and n'' are large, the ratio b_n'/b_n'' is 1.

Such a method of reasoning has been employed by the author recently[14], in a study of the temperatures of the Wolf-Rayet stars of the carbon sequence. The hydrogenic transitions in C IV identified by Edlen[15] in the Wolf-Rayet stars of the carbon sequence were employed. The transitions 7 – 10, 7 – 12, 7 – 15, 7 – 16 having wavelengths 5470·8 Å, 4229·2 Å, 3566·9 Å and 3450·5 Å can be seen well on spectrograms of the WC stars. The ratio $b_n'b_n''$ is taken as unity and the transition probabilities were calculated from the equivalent hydrogen case. A mean value of 49000° K is obtained for the WC 7 star HD 192103 and that obtained for the WC 8 star HD 184738 is

27000° K. The temperatures are estimated to be accurate within a range of ±10000°, on the basis of the accuracy of the measured emission line equivalent widths.

Having calculated the excitation temperatures of the C IV emitting region, the helium intensities measured at 4200 Å and 4542 Å were utilized to derive the b_9/b_{11} ratio for helium. These turned out to be 1·073 and 1·025 for HD 192103 and HD 184738 respectively, thus showing that collisional excitation plays an important role in the production of emission lines in Wolf-Rayet atmospheres.

Investigation of Binaries That Have Wolf-Rayet Components

Since collisional excitation seems to be a very prominent factor in the formation of the emission lines we naturally ask whether a positive excitation gradient exists in the atmosphere similar to that encountered in the solar corona and chromosphere where the excitation in the atmosphere increases as one goes outwards from the photosphere. The possible testing grounds are naturally the binary systems which are eclipsing in nature and which have a Wolf-Rayet component too. Well known systems of this kind are HD 193576 and HD 214419 which have periods of 4·2 days and 1·64 days respectively. However, various investigations carried out on these binaries have shown that a clear cut answer to these problems is not easily available from studies of just these two systems. The ideal system would be that which possesses a large period and which has not only an inclination close to 90° but also a companion relatively cooler than the Wolf-Rayet star. The long period is necessary so that distortion effects may be a minimum because of the large separation of the two components. The low temperature for the companion is required so that radiative excitation by it could be neglected. An inclination close to 90° assures the occurrence of an annular or total eclipse which would really give a clear cut picture of the eclipsed envelope of the Wolf-Rayet star. Such a system is not yet known and, therefore, it is very important that efforts be made to discover more binary systems among Wolf-Rayet stars so that such a system could be found.

All close binary systems wherein the components fill in the zero-velocity surface, necessarily have gaseous masses in motion around them thus giving rise to complicated structures in the absorption and emission spectrum. Particularly in Wolf-Rayet atmospheres where we visualise the emission envelope to be a very distended atmosphere, it is very probable that the envelope will overflow the zero-velocity surface. In fact observations carried out on HD 193576 and HD 214419 by the writer and others, indicate clearly the peculiar effects present in these two binary systems. An interesting feature in the 1·64 day system of HD 214419 is that the intensity of He II 4686 A is greatest at times of both primary and secondary minima. Sinvhal and the author [16] have found photographically from spectra a similar behaviour for the lines He II 6560 Å, He I 5875 Å, He II 5411 Å, N IV 4058 Å. Very recently [17] we have measured photoelectrically through interference filters the intensity variation of 4861 Å and 5411 Å and found that the results obtained confirm those obtained previously by photographic spectrophotometry. Such a behaviour is contrary to our experience in integrated light. A common emission envelope will explain these results, for if the emission arose in the common shell a larger portion of it would be occulted during elongations than during conjunctions. Such a common emission envelope hypothesis has been suggested earlier [16].

The segregation of Wolf-Rayet stars into two sequences has been discussed earlier. Theoretically two explanations for the existence of such carbon rich and nitrogen rich stars are possible. The first is a real abundance difference in the emission envelope caused by the rapid mixing of the products formed by nuclear transformations in the interior. The second possibility is the role of selective excitation mechanisms which might possibly affect the nitrogen lines more than carbon lines and vice-versa. While the abundance difference approach is theoretically possible, it should be adopted only after a thorough examination of selective excitation mechanisms in the far ultra violet.

In general our understanding of the nature of the Wolf-Rayet atmosphere is still in its initial stages. Much experimental and theoretical work is required before we can say with confidence that our information on these objects is atleast equal to what we possess about the normal stars.

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