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3. Wolf-Rayet star atmospheres (David C. Abbott)

Introduction. Wolf-Rayet (WR) stars are the helium-burning remnants of massive stars (initial mass $\gtrsim 30\ M_\odot$), which have lost their outer hydrogen-rich layers through the processes of Roche lobe overflow to a companion or mass loss by a strong stellar wind. The characteristic emission-line spectrum which defines the WR spectral type is produced by a stellar wind that is so dense and opaque, that the radiation of all lines and continua arise from material in the wind. Because the wind completely screens any radiation emitted by the hydrostatic core of the star, the spectra of WR stars are nearly impossible to interpret quantitatively, and the basic parameters -- such as mass, luminosity, temperature, and chemical composition -- are poorly determined.

Model Atmospheres for Wolf-Rayet Stars. Classic model atmospheres are clearly inappropriate for WR stars because of the flagrant violation of hydrostatic equilibrium and planeparallel geometry. There is no analog to the "photospheric analysis" of OB stars, which yields T_{eff}, log g, chemical composition, and the continuum radiation field. Spectral lines formed in the winds of WR stars cannot be analyzed empirically like their OB star counterparts (e.g. Castor and Lamers 1979) because: (i) Collisional processes cannot be ignored in the statistical equilibrium, as evidenced by the large observed ratio of emission to absorption in the P Cygni profiles. (ii) Radiative rates are not known a priori because the continuum radiation field depends on the run of both density and temperature in the wind. (iii) Almost all wind profiles overlap in frequency with other wind lines because of the Doppler-shift imposed by the expansion velocities. Photons of a given frequency will scatter multiply with several distinct lines in the wind, so the statistical equilibrium of different elements is interlocked by the radiation field.

Given these formidable difficulties it is no wonder that, to my knowledge, no line profile of a WR star has ever been fitted by a theoretical model to derive quantitative knowledge about the atmospheric structure. The basic means of interpreting WR winds remains the escape probability formalism of Castor and Van Blerkom (1970), in which the statistical equilibrium is solved at a "representative point" in the wind. This method essentially fits the total intensity of the observed lines, but does not utilize any information available in the line shape.

Fortunately, progress in the analysis of WR spectra appears imminent. At least three researchers are developing diagnostic models which are intermediate between present crude models and the prohibitive solution of the general problem. All use a semiempirical approach, in which $T(r)$ and $\rho(r)$ are assumed, and the radiation

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field and the statistical equilibrium of helium are then solved. Hamann (1984) solves the statistical equilibrium with the "equivalent two-level atom" method and the radiative transfer with the co-moving frame formalism. Hillier (1983) uses the complete linearization method and a hybrid of the co-moving frame and Sobolev formalisms. Schmutz (1984) uses a lambda iteration method and Sobolev formalism. A major difficulty for all these techniques is the extremely high opacity of the Lyman transitions of He II, which evidently can make convergence elusive.

Model-Independent Atmospheric Diagnostics. Until the above theory is refined to the point of application, progress in understanding WR atmospheres resides in observational diagnostics which are model-independent, or at least do not require $T(r)$ or $\rho(r)$ for their interpretation. The following are examples of studies of this type:

Absolute Magnitudes. WR stars identified with either galactic clusters (e.g. Lundström and Stenholm 1984) or with the Magellanic Clouds (e.g. Prévot-Burnichon et al. 1981; Massey and Conti 1983) have yielded values of the absolute magnitude, M_V, for 38 galactic and 38 LMC stars which are thought to be single. There is a definite trend for the later spectral subtypes to be the brightest visually, however, the dispersion in M_V at a given subtype can be as large as three magnitudes.

Line Strengths. A systematic study of the equivalent widths of the optical emission lines of He, C, N, and O is given by Conti, Leep and Perry (1983) for the WN sequence and Torres and Conti (1984, and in preparation) for the WC sequence. The dispersion in line strengths is a factor of 10 for a given WN subtype, while the dispersion for the WC subtypes is smaller, but still real.

Colors. Massey (1984) has acquired absolute spectrophotometry of 55 galactic WR stars. He constructed color-color indices to describe the intrinsic shape of the continuum which should be independent of interstellar reddening. (See, however, the anomalous interstellar extinction found by Garmany, Massey and Conti 1984.) Massey (1984) concludes that the differences in the intrinsic colors of WR stars from subtype to subtype is small compared to the considerable variation present among stars of the same subtype.

Mass. Model-independent estimates of stellar mass are possible in WR stars that are members of spectroscopic binaries. The observation and analysis of such systems is now essentially complete for the bright galactic systems (e.g. Massey 1982). Again, there is a large range in observed stellar masses, ($50\ M_\odot \gtrsim M_{WR} \gtrsim 8\ M_\odot$), with no particular correlation between mass and spectral type.

Rate of Mass Loss. Surprisingly, the mass loss rate $\dot{M}$ of the wind can be measured quite reliably by infrared/radio techniques, despite our ignorance of the underlying properties of the star (e.g. Barlow, Smith and Willis 1981; Bieging, Abbott and Churchwell 1982). There are now 22 WR stars with reliable rates from radio observations (Abbott 1984). The rates for WR stars are confined to the range $10^{-4} \gtrsim \dot{M} \gtrsim 10^{-5}\ M_\odot\ yr^{-1}$ with no correlation between $\dot{M}$ and spectral type, binarity, V_∞, or M_V. At a given spectral subtype the dispersion in $\dot{M}$ is as much as a factor of 5.

The unifying factor in all of these studies is the conclusion that spectral type is a hopelessly inadequate description of a Wolf-Rayet star. This is not surprising, as spectral classification in WR stars is one-dimensional in contrast to the two-dimensional MK scheme used for OB stars. The development of the WR analog to the luminosity class of OB stars is a necessity for the proper description of WR spectra. An interesting possibility is that the differences between stars of the same subtype arise from differences in their evolutionary history (e.g. Maeder 1982), although it is not clear at present how one can parametrize "history". Abbott and Hummer (1984) have shown that the "photospheric" spectrum of OB stars can depend as strongly on $\dot{M}$ as on the traditional parameters of T_{eff} and gravity. Given the overwhelming strength of WR winds, the mass loss rate will doubtless also become an important third parameter for describing WR spectra.

Chemical Composition of WR Atmospheres. One quantity sure to correlate with spectral type is chemical composition. The two classification sequences of WR stars represent atmospheres enhanced with the products of hydrogen burning (WN sequence) and with the products of helium burning (WC sequence). While the composition

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anomalies of WR stars are obvious from even a cursory examination of the spectra, efforts to derive quantitative values of composition have been hampered by the lack of model atmospheres. The best estimates probably come from the escape probability formalism, which yields [C/N] and [N/He] ratios generally in accord with predictions from stellar evolution calculations (e.g. Smith and Willis 1982).

The hydrogen abundance of WR atmospheres is estimated in a fairly model-independent manner by comparing optical emission-line strengths between lines of the He II Pickering series which do, and do not, overlap with the H I Balmer series. Previous work has established that WR stars are hydrogen deficient, although severe blending makes this method questionable for the WC sequence. Recently, this method was used by Conti, Leep and Perry (1983) to derive quantitative estimates of the |H/He| ratio in 37 galactic and 20 LMC stars of the WN type. Hydrogen is present in roughly 1/3 of the stars, typically of a level of H/He ≈ 1-2 by number.

Conclusive evidence for the presence of hydrogen in some WR atmospheres has come from radial velocity studies that prove that the hydrogen absorption lines in some WR + O binaries are intrinsic to the WR star (e.g. Niemela 1979). Interestingly, several "single" WR stars (i.e. radial velocity variations $\lesssim 15$ km s^{-1}) also show weak hydrogen absorption lines (e.g. Massey, Conti and Niemela 1981). The lines are either intrinsic or belong to a very distant companion (period $\gtrsim$ 500 days). If intrinsic, these stars would include the first definite proof that hydrogen exists in the WC sequence.

V444 Cygni: The Anatomy of a WR Atmospehere. A fantasy of any astronomer studying WR stars would be to have a movable probe in the atmosphere which could directly measure density, temperature and composition. Probably the closest realization of this dream we will ever have is the eclipsing binary system V444 Cygni (WN5+06). As demonstrated by Cherepashchuk, Eaton and Khaliullin (1984), measurements of the eclipse duration and strength for a wide range of lines and continuum frequencies provide a direct measurement of both the intensity of the radiation and the opacity as a function of radius. Further, the measured period change gives a model-independent diagnostic of $\dot{M}$. With such an analysis, Cherepashchuk et al. conclude that:

(i) The atmosphere is composed of a compact ($R_C \sim 3\ R_\odot$), hot ($T_B \sim 10^5$ K) core surrounded by an extended envelope characterized by a decreasing temperature gradient ($T_e \sim 10^4$ K at 8 $R_\odot$).

(ii) The concept of T_{eff} is ill-defined because the "photospheric" radius is a strong function of wavelength. The bulk of the radiation flow is emitted at small radii, which implies that by any definition T_{eff} exceeds 90,000 K.

(iii) The outflow velocity at the stellar core [$\tau_e(R_c) \sim 1$] is roughly 400 km s^{-1}, which verifies that the continuum is formed in an expanding, spherical region. The wind rapidly accelerates to ≈ 2500 km s^{-1} between 3 $R_\odot$ and 8 $R_\odot$.

Do WR Atmospheres Pulsate? Wolf-Rayet stars are at or near the theoretical limit for vibrational instability (e.g. Maeder 1984). The possible consequences of pulsation on the structure of the atmosphere remain largely unexplored, mainly because there has been no observational confirmation that the oscillations actually exist. Recently, Vreux (1984) reanalyzed the time variability of the class of "WR + compact companion" binary systems, and he argues that the observed radial-velocity variations are most likely nonradial oscillations in single stars. If this conclusion is verified by further observations, it raises exciting possibilities for the diagnostics of stellar properties from observed periods and modes, and for the study of the interaction between pulsations and stellar winds.

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4. White Dwarf Atmospheres (Rainer Wehrse)

Introductory Remarks. The main characteristic of white dwarf atmospheres is a pressure that is at least two orders of magnitude higher than in main sequence star atmospheres of the same effective temperature. This is due to the high gravity (log $g \simeq 8$), extreme metal under-abundances ($\Delta \log \varepsilon_M \gtrsim 2.5$), and (in many cases) the replacement of hydrogen by helium as the main constituent. As consequences the atmospheres are very thin ($\Delta R \lesssim$ a few km) and the level populations of all species are given by the Boltzmann distribution (perhaps with the exception of the extreme outer layers, Greenstein 1973, Pilachowski 1984). Thus, models can be calculated under the assumption of plane parallel radiative transfer and local thermodynamic equilibrium , which facilitates the numerics very much; but special care has to be taken of pressure effects (e.g., broadening of spectral lines, quenching of levels, changes in the dissociation-ionization equilibria). In addition, the proper consideration of convection, which is very effective and may reach into the optically thin layers, makes the construction of model atmospheres for white dwarfs rather tedious and costly.

Mainly due to the work of Greenstein (see e.g. his paper on spectrophotometry, Greenstein 1984) and R. Green (see Green, Schmidt and Liebert 1984) the empirical basis for studying white dwarf atmospheres has recently widened very much. The new edition of the McCook-Sion catalogue (1984) contains about 1500 white dwarfs for which photometric, spectroscopic and/or astrometric data are available. Most of them are classified in the new system of Sion et al. (1983).

In the following, I want to review some selected aspects of the progress in the understanding of white dwarf atmospheres following the last extensive review (Liebert 1980). However, due to the lack of space, I will not cover the interesting effects of magnetic fields (for a review see Borra, Landstreet and Mestel 1982) and variability (see Winget and Fontaine 1982), nor discuss white dwarfs in close binary systems (see proceedings of IAU Colloquium no. 72).

Spectroscopy in the Ultraviolet. The use of the IUE satellite has revealed the existence of several interesting and unexpected features in the UV spectra of white dwarfs. The most important seem to be:

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