OBSERVATIONS OF THE ATMOSPHERES AND WINDS OF O-STARS, LBVS AND WOLF-RAYET STARS

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Abstract. This review summarises recent studies of O-stars, Luminous Blue Variables (LBVs) and Wolf-Rayet (WR) stars, emphasising observations and analyses of their atmospheres and stellar winds yielding determinations of their physical and chemical properties. Studies of these stellar groups provide important tests of both stellar wind theory and stellar evolution models incorporating mass-loss effects. Quantitative analyses of O-star spectra reveal enhanced helium abundances in Of and many luminous O-supergiants, together with CNO anomalies in OBN and Ofpe/WN9 stars, indicative of evolved objects. Enhanced helium, and CNO-cycle products are observed in several LBVs, implying a highly evolved status, whilst for the WR stars there is strong evidence for the exposition of CNO-cycle products in WN stars, and helium-burning products in WC and WO stars. The observed wind properties and mass-loss rates derived for O-stars show, in general terms, good agreement with predictions from the latest radiation-driven wind models, although some discrepancies are apparent. Several LBVs show similar mass-loss rates at maximum and minimum states, contrary to previous expectations, with the mechanism responsible for the variability and outbursts remaining unclear. WR stars exhibit the most extreme levels of mass-loss and stellar wind momenta. Whilst alternative mass-loss mechanisms have been proposed, recent calculations indicate that radiation pressure alone may be sufficient, given the strong ionization stratification present in their winds.

Key words: stars:winds -- stars:mass-loss -- stars:evolution -- stars:abundances -- stars:Wolf-Rayet -- stars:atmospheres

1. O Stars

We review progress in observational and interpretative studies of O-stars, concentrating on determinations of their stellar wind and mass-loss properties and atmospheric chemical composition. More general reviews of this field has been given in Conti & Underhill (1988), whilst Kudritzki & Hummer (1990) have given a review describing progress in quantitative spectroscopy of hot, early-type stars.

1.1. Mass-loss rates and wind velocities

Observational studies over the past decade have used data across the electromagnetic spectrum to characterise the wind properties and mass-loss rates of massive stars, provide tests of radiation-driven wind theory (e.g. Pauldrach et al, 1986, 1990), and the mass-loss parameterizations used in stellar evolution models (e.g. Maeder, 1990).

Bieging et al (1989) have summarised radio observations at 2, 6 and 20 cm of
Galactic OB stars. For 7 sources (confined to the most luminous stars, $\geq 10^6 L_\odot$) with detected radio emission and confirmed as thermal, free-free emitters, they derive mass-loss rates of $\sim 10^{-5} M_\odot \text{yr}^{-1}$. Leitherer & Robert (1991) report the detection of 4 OB stars at 1.3 mm, finding mm–radio spectral indices of $\sim 0.6$, consistent with free-free emission expectations, and confirming the radio mass-loss rates. Determinations of $\dot{M}$ for larger stellar samples have generally relied on analyses of UV and/or Hα observations.

Howarth & Prinja (1989) analysed the UV P–Cygni profiles in the IUE spectra of 203 Galactic OB stars, using the radio-derived mass-loss rates to estimate empirical ionization fractions in the stellar winds. They derive a well-defined relation between mass-loss rate and stellar luminosity:

$$\log \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) = 1.69 \log \left( \frac{L}{L_\odot} \right) - 15.4$$

finding good agreement with predictions of finite disk, steady state wind models. In an earlier study of the UV spectra of 16 OB stars, Garmany & Conti (1984) deduced a similar scaling: $\dot{M} \propto L/L_\odot^{1.62}$. This relation was used by Leitherer (1988) to calibrate mass-loss rate with observed Hα emission measured in 149 Galactic OB stars, with the wind velocity law derived ($\beta \sim 0.7$) agreeing with the value of $\beta \sim 0.8$ predicted from the wind models of Pauldrach et al (1986).

Groenenwegen & Lamers (1989) analysed the UV P–Cygni profiles in 26 O–stars using the SEI method, including allowance for turbulence in the winds, and derived a velocity law with $\beta = 0.68 \pm 0.15$ in good agreement with theory.

Groenenwegen & Lamers (1991) find that the empirically-derived ionization ratios in Si iv, C iv and N v, show very large differences (factors of 100-1000) with those predicted in the wind models of Pauldrach et al (1990) and Drew (1989), whilst Groenenwegen et al (1989) find that the O–star wind terminal velocities derived from UV profile fitting are systematically lower by about 40% than predicted. They find $v_\infty / v_{\text{esc}} = 2.78 \pm 0.36$ – independent of luminosity class – compared to the value of about 3.9 expected from Pauldrach et al (1990) theory. Similar conclusions are found by Blomme (1990), and also by Prinja et al (1990) who measure $v_\infty$ in a sample of 150 O-stars from the violet limit of saturated troughs in UV P–Cygni absorption profiles, and derive a mean ratio of $v_\infty / v_{\text{esc}} = 2.41$. This discrepancy suggests either some remaining inadequacy in the radiation pressure models or some systematic error in the stellar parameters derived from the evolutionary tracks which are used to determine $v_{\text{esc}}$. To shed light on this question, Lamers & Leitherer (1993) have re–derived mass-loss rates for 28 Galactic OB stars utilising radio and Hα data, finding:

$$\log \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) = 1.738 \log \left( \frac{L}{L_\odot} \right) - 1.352 \log T_{\text{eff}} - 9.547$$

in good agreement with the scale adopted by Maeder (1990) in computing evolutionary tracks for OB stars. The empirical mass-loss rates are higher by about a factor of two than values predicted in the wind models. Lamers & Leitherer suggest that this discrepancy (particularly evident in the most luminous stars) may be a reflection, at a more modest level, of additional mechanisms (e.g. multiple scattering) required to explain the high mass-loss rates and wind momenta.