P V and the Mass Loss Discrepancy in O Stars

D. Massa
SGT, Inc.
Code 681, NASA’s GSFC, Greenbelt, MD 20901, USA

A.W. Fullerton
University of Victoria & Johns Hopkins University
3400 N. Charles St., Baltimore, MD 21218, USA

R.K. Prinja
Department of Physics & Astronomy, UCL
Gower Street, London WC1E 6BT, UK

Abstract. Building upon a previous analysis of P V wind lines in LMC O stars, we analyze the P V wind lines in a sample of Galactic O stars which have empirical mass loss rates determined from either their radio fluxes or Hα profiles. Since the wind analysis provides a measure of \( \dot{M} q \) where \( q \) is the ionization fraction of the ion, we determine \( q(\text{P V}) \) observationally. In spite of model predictions that \( q \sim 1 \) for mid-O stars, we find \( q(\text{P V}) \leq 0.15 \) throughout the O stars. We discuss the origin of this discrepancy.

1. Measures of \( \dot{M} \)

Three approaches are normally used to determine stellar mass loss rates, \( \dot{M}s \).
All assume that the wind is homogeneous and spherically symmetric (SS) with a single, monotonic velocity law, and all should agree. The three approaches are:

1. Continuum excess from free-free emission. This samples the outer wind (the exact radius depends on wavelength), where it becomes optically thick to free-free emission. It is only detectable for massive winds in nearby stars. The radio wavelengths are considered “cleanest”, because, in contrast to the IR/FIR, massive winds become optically thick at large radii (\( \geq 10R_* \)), where \( v = v_\infty \), a constant. This makes \( \rho_{\text{wind}} \sim \dot{M}/(r^2v_\infty) \), independent of \( v(r) \). Furthermore, no photospheric correction is needed. However, the radio flux can be non-thermal, so observations at multiple wavelengths are required to determine the spectral index of the emission.

2. Hα emission. This samples the inner wind and is easily observed. For massive winds, Hα emission is related to \( \dot{M} \). However, the exact form of the observed Hα profile depends upon the \( N = 3 \) departure coefficient for H in the wind and this, in turn, depends upon: the photospheric radiation field; the diffuse radiation field of the wind; and the wind velocity law in the acceleration region. The shape of the “photospheric” Hα profile is also required, and the observed \( W_\lambda(H\alpha) \) can be strongly variable. Nevertheless, relatively sophisticated models
for Hα formation exist (e.g., Repolust et al. 2004), and can provide reasonable agreement between available radio and Hα Ṁs when Hα emission is strong.

3. UV resonance lines. These sample the entire wind. Their shapes are determined by the radial optical depth of the wind, \( \tau_{\text{rad}} \sim \dot{M} q_i A_E \), where \( A_E \) and \( q_i \) are the abundance of element \( E \) and its ionization fraction for stage \( i \). However observations of a dominant ion (\( q_i \sim 1 \)), of known abundance are required to estimate \( \dot{M} \) directly, and the wind lines of abundant, dominant ions are saturated in winds massive enough to be detected in the radio or to have reliable Hα Ṁs.

2. FUSE and P V

\textit{FUSE} gives access to P V \( \lambda\lambda 1118,1128 \). P V is a surrogate for C iv (Massa et al. 2003) and \( q_i \sim 1 \) is expected for both ions in mid-O star winds. Unlike \( A_C \), \( A_P = \text{Const} \) over the life of an O star. Furthermore, for scaled solar abundances, \( \tau_{\text{rad}}(\text{C IV})/\tau_{\text{rad}}(\text{P V}) = 661 \), so to detect P V, \( \tau_{\text{rad}}(\text{C IV}) \geq 50 \) and saturated – as is the case for stars with detectable radio fluxes and strong Hα emission.

\textbf{P V in LMC O Stars:} The first large scale \textit{FUSE} study of P V was by Massa et al. (2003). They performed SEI (Lamers et al. 1987) fits to P V wind lines, determining \( \tau_{\text{rad}} \) for 25 LMC O stars. They then used \( \dot{M} \)s predicted by the Vink et al. (2001) theory and \( A_P = 0.50\times\text{solar} \) to find that \( q(P \text{ V}) \) peaked between 45–50 kK, as expected, but with a peak value \( \leq 0.15 \) (see Fig. 1). This result implies a factor of 7 or more discrepancy between the expected and observed \( \dot{M} \)s. There are three possible explanations for this result:

1. The LMC P abundance scales differently from other elements,
2. The theoretical \( \dot{M} \)s are incorrect for the LMC, or
3. The winds are not homogeneous and SS, but strongly clumped or structured.

\textbf{P V in Galactic O Stars (preliminary results):} The Galactic \( A_P \) is well determined (e.g., Catanzaro et al. 2003), so abundance is not an issue for the Galaxy. We are currently analyzing P V in \textit{Copernicus, Orfeus} and \textit{FUSE} data for stars with radio and/or Hα \( \dot{M} \) estimates. This eliminates the need for model \( \dot{M} \)s to derive \( q \) for P V, and determines how well different mass loss rate indicators agree. So far, we have analyzed 30 stars (11 more will be observed by \textit{FUSE}), and the results are shown in Figure 2. These results are effectively identical to those from the LMC (Fig. 1), implying the same conclusions.

3. Conclusions

- An erroneous P abundance is not the cause of the small LMC \( q(P \text{ V}) \)s.
- Strong clumping/porosity must be the root of the problem.
- Large scale clumping can also strongly affect the radio and Hα \( \dot{M} \)s, so these should be re-evaluated.
- The good news: the different measures of \( \dot{M} \) are sensitive to different aspects of the wind flow, so bringing them all into agreement (together with the X-ray and O vi wind line observations) will provide powerful constraints on models of how the winds are structured.
Figure 1. Mean $P\nu$ ionization fractions as a function of temperature for LMC O stars analyzed by Massa et al. (2003). Open, half filled and filled symbols denote stellar luminosities in the ranges $\log L/L_\odot > 6.0$, $6.0 \geq \log L/L_\odot > 5.6$ and $5.6 \geq \log L/L_\odot$, respectively.

Figure 2. Mean $P\nu$ ionization fractions versus temperature for Galactic O stars with radio or Hα $\dot{M}_s$. Filled symbols: radio $\dot{M}_s$, open circles: Hα $\dot{M}_s$ from Repolust et al. (2004), open triangles: Hα $\dot{M}_s$ from Lamers & Leitherer (1993).

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