Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L.M. Oskinova, eds.
Potsdam: Univ.-Verl., 2008
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

Revised mass-loss rates for O stars from the P v resonance line

A. W. Fullerton[1], **D. L. Massa**[2] & **R. K. Prinja**[3]
[1] *Space Telescope Science Institute, USA*
[2] *SGT, Inc., NASA Goddard Space Flight Center, USA*
[3] *University College London, England*

The P v $\lambda\lambda1118, 1128$ resonance doublet is an extraordinarily useful diagnostic of O-star winds, because it bypasses the traditional problems associated with determining mass-loss rates from UV resonance lines. We discuss critically the assumptions and uncertainties involved with using P v to diagnose mass-loss rates, and conclude that the large discrepancies between mass-loss rates determined from P v and the rates determined from "density squared" emission processes pose a significant challenge to the "standard model" of hot-star winds. The disparate measurements can be reconciled if the winds of O-type stars are strongly clumped on small spatial scales, which in turn implies that mass-loss rates based on Hα or radio emission are too large by up to an order of magnitude.

1 Diagnostics of mass loss

Wind profiles of the resonance lines of ionized metals are the most sensitive indicators of the outflows from hot, massive stars because they are caused by the scattering of photons by individual particles. However, resonance lines cannot generally be used for quantitative measurements of the mass flux, because the strength of the absorption trough of a P Cygni profile only determines $\dot{M}q$, where $\dot{M}$ is the mass-loss rate and q is the ion fraction of the species. Consequently, resonance lines provide direct determinations of $\dot{M}$ only when they are due to the dominant ion of an element (i.e., $q \approx 1$).

Unfortunately, estimating q for any given resonance line is problematical. Of course, ion fractions can be predicted via detailed modelling, e.g., with `CMFGEN` or `FASTWIND`, but the overall reliability of these predictions depends on other, poorly constrained factors and assumptions, e.g., concerning X-rays, line blanketing/blocking, etc.. Ion fractions cannot be determined empirically, since access to resonance lines from consecutive stages of ionization is not generally available in the far-UV and UV regions. Finally, even in cases where a particular ion of an abundant element is expected to be dominant (e.g., C^{3+} in mid- to late-O stars), the resonance line is almost always saturated, so that even in these favorable cases only lower limits to the amount of material in the wind can be estimated. As a result, mass-loss determinations have relied on recombination lines (particularly Hα) or free-free radio emission. In contrast to scattering, these processes require the interaction of two particles; i.e., they are "density squared" ("ρ^2") processes.

However, the P v $\lambda\lambda1118,\ 1128$ resonance doublet accessible to *FUSE* side-steps the traditional problems associated with metallic resonance lines, essentially because the cosmic abundance of P is so low that the doublet is not saturated even when P^{4+} is the dominant ion. Consider, e.g., that in the Sun the abundance of P is ~0.09% of the abundance of C! As illustrated in the *FUSE* atlases of Galactic and Magellanic OB spectra (Pellerin et al. 2002; Walborn et al. 2002), the doublet is very weak for the earliest O spectral types, exhibits a broad maximum, and then weakens substantially between O9.5 and B0. This behavior is consistent with the ion fraction of P^{4+} achieving a maximum for mid O-type stars. Model atmosphere calculations suggest that P^{4+} is the dominant ion of P in the outer winds of stars with temperature classes between ~O7.5 and O9.7.

2 The P v problem

If $q(P^{4+})\approx 1$ for some range of O temperature classes, then measurements of the strength of its P Cygni profile should provide an independent estimate of $\dot{M}$, which can be compared with precise values determined from radio or Hα measurements. Fullerton et al. (2006) performed this comparison for a carefully selected sample of 40 Galactic O stars, all of which have well-determined values of $\dot{M}$ from "ρ^2" diagnostics. Fits to the wind profiles provide reliable estimates of the radial optical depth of a wind, while requiring a minimal number of assumptions beyond those of the "standard model". For a given velocity law (which can be constrained by fitting wind profiles of saturated resonance lines), the optical depths are directly related to mass-loss rates via:

$$\tau_{rad} \propto \dot{M}\, q(\mathrm{P}^{4+})\, A_P \qquad (1)$$

where A_P is the assumed abundance of P relative to H by number.

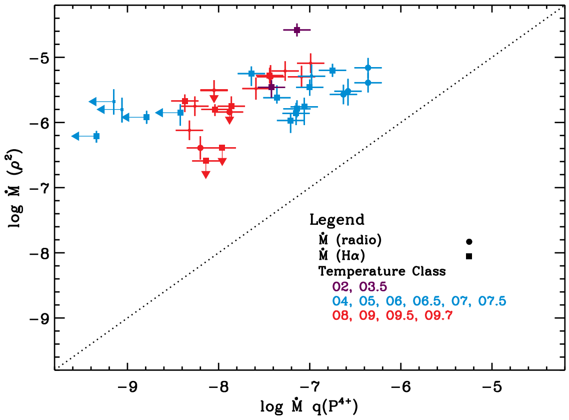

Figure 1: Comparison of $\dot{M}(\rho^2)$ with $\dot{M}q(\mathrm{P}^{4+})$. From Fullerton et al. (2006).

Figure 1 shows that $\dot{M}q(\mathrm{P}^{4+})$ is typically less than $\dot{M}(\rho^2)$ by a factor of ∼10 for mid-range O stars, and by substantially larger factors for earlier and later spectral types. Contrary to expectations, the two mass-loss indicators *never* agree with each other, even though both are determined precisely.

Of course, we did not expect agreement for all stars in our sample. Since the empirical behavior of the P V doublet suggests that the $q(\mathrm{P}^{4+})$ is largest for mid-range O-stars, we thought that the diagnostics would be within a factor of ∼2 for these objects, and that discrepancies for the earliest and latest spectral types would be due to the fact that $q(\mathrm{P}^{4+})$ is small. However, for these mid-range stars, the median discrepancy $\dot{M}(\rho^2)/\dot{M}q(\mathrm{P}^{4+}) = 20$. If "standard" model atmospheres correctly predict the range of spectral types where (P^{4+}) is the dominant ion, the median discrepancy is a factor of ∼130. This discrepancy is the "P V problem".

3 Re-examining assumptions

Since the implications of this discrepancy are significant, a critical assessment of the assumptions associated with the measurements of the P V resonance line is in order. Eq. (1) shows that there are three assumptions that affect the interpretation of τ_{rad}: (a) a value of A_P is assumed; (b) it is assumed that $q(\mathrm{P}^{4+}) \approx 1$ for some range of O temperature classes; (c) the structure of the wind is described by the "standard model", which assumes that the wind is spherically symmetric, homogeneous, and stationary with a monotonically increasing velocity law.

3.1 The Galactic abundance of P

Fullerton et al. (2006) assumed a solar abundance for P. A smaller abundance would shift points in Fig. 1 to the right and reduce the discrepancy. However, there is no evidence to support a reduction of the magnitude required. On the contrary, analysis of P II lines in the diffuse interstellar medium (e.g., Lebouteiller et al. 2005, and references therein) confirm that the abundance of P is solar along several lines of sight. Since this is the raw material from which O stars form, and since the abundance of P is not altered by nuclear processes over the evolutionary lifetime of a star, there is no reason to suspect that the abundance of P is systematically subsolar. Further support is supplied by the persistence of the "P V problem" for O stars in the Large Magellanic Cloud (Massa et al. 2003); i.e., in an environment with a globally reduced metallicity.

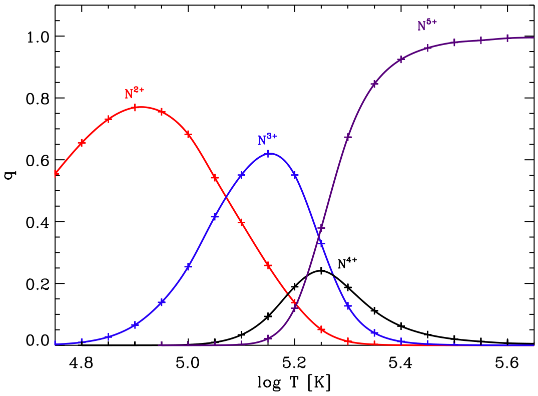

Figure 2: The collisional ionization equilibrium for nitrogen (Sutherland & Dopita 1993).

3.2 Is the maximum value of $q(\mathrm{P}^{4+})$∼1?

By asserting that $\dot{M} \approx \dot{M}q(\mathrm{P}^{4+})$ for *some* range of temperature classes, we are explicitly assuming that the ion fraction of $\mathrm{P}(^{4+})$ peaks near unity. Although Fig. 4 of Fullerton et al. (2006) suggests that the ion fraction goes through a maximum for mid-range O stars, the value of the peak is not known a priori. This is a serious concern, since species with one valence electron like $\mathrm{P}(^{4+})$ typically exhibit maximum ion fractions that are substantially less than 1 in calculations of collisional equilibria. Fig. 2 illustrates this "fragility" in the case of N^{4+} (which is the analog of P^{4+} in the preceding row of the periodic table), by indicating a peak value of $q(\mathrm{N}^{4+}) \sim 0.2$. The obvious counter-argument is that the ionization balance in hot-star winds is dominated by photoionization, not collisions; and more relevant models (computed, e.g., with `FASTWIND` or `CMFGEN`) show that $q(\mathrm{P}^{4+})$ does indeed approach unity over much of the wind for stars of the appropriate temperatures; see, e.g., Puls et al. (2006).

The basic problem is that we simply do not know a priori how $q(\mathrm{P}^{4+})$ varies in the winds of O-type stars. Model atmosphere calculations provide valuable guidance, although a variety of issues connected with the ionization equilibrium of stellar winds must be resolved. Despite these uncertainties, there is at present no reason to suspect that the mean ion fraction of P^{4+} is always less than $\sim$0.1 for O stars, as would be required to explain the discrepancy.

3.3 Resolution: Relaxing the assumptions of the standard model

The only remaining assumptions associated with the P v analysis define the “standard model”, which forms the basis of the determination of $\dot{M}$ by any of the usual techniques: sphericity, homogeneity, stationarity, and monotonicity. To resolve the “P v problem”, at least one of these assumptions must be relaxed. However, relaxing any of them is tantamount to acknowledging that the density structure is inhomogeneous. Thus, the discrepancy between $\dot{M}(\rho^2)$ and $\dot{M}q(\mathrm{P}^{4+})$ signals that the winds of O stars are inhomogeneous, or “clumped”.

The spatial scale associated with the clumps is not known: a variety of scales may be involved, since the winds of many O-type stars are structured on large scales (as indicated, e.g., by the presence of discrete absorption components). Optically thin clumps (which have spatial scales that are smaller than the mean free path of a photon) are easily incorporated in stellar atmosphere models, and permit progress to be made despite uncertainties concerning the mechanism(s) responsible for generating structure in the wind (though the line-driven instability is certainly implicated). In the optically thin limit, the discrepancy between $\dot{M}(\rho^2)$ and $\dot{M}q(\mathrm{P}^{4+})$ is resolved by recognizing that ρ^2 diagnostics are inherently biased: in the presence of clumps, they *systematically over-estimate* mass-loss rates if they are modelled with the assumptions of the “standard model”. Thus, a fundamental consequence of clumping in hot-star winds is that the values of $\dot{M}(\rho^2)$ *must be reduced.* The only question is: by how much? If the entire discrepancy is assigned to this effect alone, then the mass-loss rates derived from ρ^2 diagnotics are too large by an order of magnitude and the clumped material must occupy a tiny fraction of the volume of the wind.

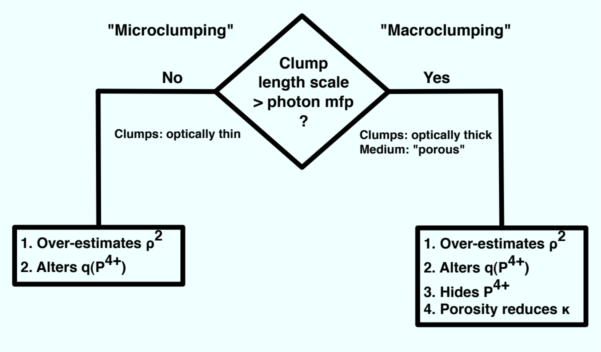

Figure 3: A schematic representation of the effects of clumping.

However, other competing factors might come into play, since density enhancements also change the ionization structure of the wind, particularly $q(\mathrm{P}^{4+})$. Furthermore, as noted by Oskinova et al. (2007), clumps may be optically thin for one diagnostic but not another; i.e., the effects of clumping are not the same for all mass-loss diagnostics. Radiative transfer through a medium in which optically thick clumps are embedded (i.e, a “porous” medium) is quite different from the case of a medium comprised of optically thin clumps. As discussed by Hamann, Townsend, Feldmeier, Oskinova, & Owocki at this workshop, porosity leads to a variety of ways of reinterpreting the observed optical depth of a resonance line. Fig. 3 provides a simplified scheme to characterize these consequences. At present it is not clear whether one of these effects dominates, or whether several of them are required to resolve the mass-loss discrepancy. Regardless, the fundamental conclusion remains: *O-star winds are clumpy.*

References

Fullerton, A. W., Massa, D. L., & Prinja, R. K. 2006, ApJ, 637, 1025

Lebouteiller, V., Kuassivi, & Ferlet, R. 2005, A&A, 443, 509

Massa, D., Fullerton, A. W., Sonneborn, G., & Hutchings, J. B. 2003, ApJ, 586, 996

Oskinova, L. M., Hamann, W.-R., & Feldmeier, A. 2007, A&A, 476, 1331

Pellerin, A., et al. 2002, ApJS, 143, 159

Puls, J., Markova, N., & Scuderi, S. 2006, preprint arXiv:astro-ph/0607290v1

Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253

Walborn, N. R., et al. 2002, ApJS, 141, 443

Cohen: Does the P IV resonance line provide any useful information about either abundances or the ionization balance in the wind?

Fullerton: For Galactic O stars, extinction usually prevents any meaningful observations of the far-ultraviolet spectrum below ~1000 Å. The situation is much more favourable for stars in the Magellanic Clouds. Even there, the P IV λ951 resonance line is badly blended with the interstellar Lyman δ line of H at 949.7 Å and the red component of the S VI doublet. So, it is not immediately obvious how it could be used to constrain the behavior of phosphorous in a wind. Despite the blending, we know P IV is present with some strength because in the two cases where we have long time series observations we can see it vary. It is an unusual situation: the variations about the mean, blended profile are present with large amplitude (larger than in P V), though we cannot even see, let alone measure, the mean profile.

Ignace: By "variable", do you mean the P IV resonance line is different across spectral types?

Fullerton: No; in this case "variable" refers to changes in the profile of the P IV resonance line of a single object. Of course, we would also expect the mean profile to change with spectral type. It is really too bad that we cannot make better use of it.

Cassinelli: You assume that P V is a dominant ion stage even inside a clump. However, as I will discuss later, the clumps have a bow shock surrounding them that produces X-rays. This intense X-ray radiation should greatly increase the ionization state in the clump via the Auger mechanism (say to P VII or P VIII), so P V would not provide a true measure of the optical depth through the wind; i.e. your ion fractions q(P V) are too large, and the mass loss rate is not necessarily reduced.

Fullerton: I think this is an interesting way of changing the ion fraction of P V within a clump. I guess that the change in the global ion fraction will depend on the competing process of recombination, which will be a function of the density and dimensions of the clump. But the upshot could very well be an overall reduction in q(P V) from dominant values, which will reduce the mass loss discrepancy, particularly if clumps represent the bulk of the wind. Of course, the basic conclusion of the analysis – that the discrepant P V-Hα mass loss rates indicate the presence of significant clumping – would remain, but with more modest decreases in the mass loss rates.

Prinja: We should note that an ionization "issue" also extends beyond the O stars and P V to B supergiants and the fact that Si IV never appears to be the dominant ion of silicon in line synthesis analysis, while models (CMFGEN, etc.) predict that it should be.

Fullerton: I think that the ionization balance in hot-star winds needs to be revisited, with particular emphasis on the effect of localized density enhancements.