THE IMPORTANCE OF XUV RADIATION AS A SOLUTION TO THE P v MASS LOSS RATE DISCREPANCY IN O STARS

W. L. WALDRON1 AND J. P. CASSINELLI2

1 Eureka Scientific Inc., 2452 Delmer Street, Oakland, CA 94602, USA; wwaldron@satx.rr.com
2 Department of Astronomy, University of Wisconsin-Madison, Madison, WI 53711, USA; cassinelli@astro.wisc.edu

Received 2009 October 20; accepted 2010 January 25; published 2010 February 11

ABSTRACT

A controversy has developed regarding the stellar wind mass loss rates in O stars. The current consensus is that these winds may be clumped, which implies that all previously derived mass loss rates using density-squared diagnostics are overestimated by a factor of \(\approx 2\). However, arguments based on Far Ultraviolet Spectroscopic Explorer (FUSE) observations of the P v resonance line doublet suggest that these rates should be smaller by another order of magnitude, provided that P v is the dominant phosphorous ion among these stars. Although a large mass loss rate reduction would have a range of undesirable consequences, it does provide a straightforward explanation of the unexpected symmetric and un-shifted X-ray emission-line profiles observed in high-energy resolution spectra. But acceptance of such a large reduction then leads to a contradiction with an important observed X-ray property: the correlation between He-like ion source radii and their equivalent X-ray continuum optical depth unity radii. Here we examine the phosphorous ionization balance since the P v fractional abundance, \(q(P v)\), is fundamental to understanding the magnitude of this mass loss reduction. We find that strong emission line radiation in the XUV energy band (defined here as 54 to 124 eV) can significantly reduce \(q(P v)\). Furthermore, owing to the unique energy distribution of these XUV lines, there is a negligible impact on the S v fractional abundance (a key component in the FUSE mass loss argument). We conclude that large reductions in O star mass loss rates are not required, and the X-ray optical depth unity relation remains valid.

Key words: stars: early-type – stars: mass-loss – stars: winds, outflows – X-rays: stars

1. INTRODUCTION

Over the past several years, questions concerning the validity of what we refer to as the “traditional” O star mass loss rates, \(\dot{M}\), have arisen owing to the predictions of clumped wind models (see recent Potsdam Workshop, Hamann et al. 2008, and references therein). Abbott et al. (1981) showed that inhomogeneous winds lead to an enhancement in density-squared emission processes such as H\(\alpha\), infrared, and radio free–free, which means that the inferred \(\dot{M}\) would be overestimated (see also Puls et al. 2006). Although a clear picture of these clumpy structures is still being developed, the so-called clumping factor \(f_{\text{cl}}\) is believed to be \(\approx 4–5\), and the reduction in \(\dot{M}\) scales with \(\sqrt{f_{\text{cl}}}\) (see the general discussion in Hamann et al. 2008).

The derived \(\dot{M}\) from diagnostics that are linearly dependent on density (e.g., analyses of unsaturated UV resonance line profiles) are expected to be independent of clumping effects (Puls et al. 2006) and supposedly should provide more reliable \(\dot{M}\) values. In fact, analyses of the P v resonance line doublet (\(\lambda\lambda 1118, 1128\) \(\AA\)) obtained from Far Ultraviolet Spectroscopic Explorer (FUSE) observations led to the conclusion that traditional \(\dot{M}\) are overestimated by a factor of 10 or more (Massa et al. 2003, hereafter M03; Fullerton et al. 2006, hereafter F06). Such reductions have far-reaching consequences. For example, Hirschi (2008) concluded that the well-known evolutionary tracks of massive stars could survive \(\dot{M}\) reductions by a factor of 2, but not by a factor of 10 or more.

Resolution of this \(\dot{M}\) problem is also of particular importance with regard to the observed X-ray emission-line properties obtained from Chandra and XMM-Newton observations. Waldron & Cassinelli (2007) analyzed the Chandra HETGS X-ray line properties for a large number of OB stars, and two of their conclusions are directly relevant to this \(\dot{M}\) issue. (1) All of the resolved X-ray emission lines are very broad (i.e., half-width at half-maximum (HWHM) range of 300–1000 km s\(^{-1}\)), symmetric, and the majority have minimal line shifts. Although Waldron & Cassinelli (2001) were the first to demonstrate that these X-ray line profiles could in fact be easily explained by a significant reduction in \(\dot{M}\), this was inconsistent with the then accepted observed \(\dot{M}\), and they suggested a clumpy or non-symmetric wind structure as a possible explanation. (2) The radial locations of the He-like forbidden, intercombination, resonance (\(f\)r) line sources, as derived from their \(f\)/i line ratios, typically range from 1.2 to 10 \(R_\odot\), and these distances are well correlated with their respective stellar wind X-ray continuum optical depth unity radii which we shall refer to as the “X-ray continuum optical depth unity relation” (hereafter abbreviated as XODUR). This relation implies that the traditional \(\dot{M}\) (like those of Vink et al. 2000) must be correct (i.e., within a factor of 2 or so). Nevertheless, large \(\dot{M}\) reductions have become a widely used explanation of the X-ray line profile symmetry problem (e.g., Kramer et al. 2003; Cohen et al. 2006) because the emission from both the near and far side of a star would be observable in an optically thin wind. The subject is not yet resolved since Oskinova et al. (2004, 2006) find that the symmetry can also be explained by accounting for the porosity of clumped (or fragmented) winds without the need for a reduction in \(\dot{M}\), but Owocki & Cohen (2006) present arguments against the porosity influence.

The primary goal of this Letter is to examine the effects of an excess of hard radiation within the He \(\alpha\) Lyman continuum on the ionization equilibrium of phosphorus by utilizing only outer shell photoionization processes. This is important since the proposed large reduction in \(\dot{M}\) is based entirely on the assumed P v fractional ionization abundance. In addition, we also consider the sulfur ionization balance because of two
arguments used by M03 and F06: (1) since phosphorous and sulfur have overlapping ranges in ionization energy, the dominant stages of sulfur can be used as surrogates for the corresponding ones of phosphorous, and (2) both P\textsuperscript{v} and S\textsuperscript{v} are likely to be the dominant ionization stages throughout the O star spectral range.

We propose that the primary source of this excess hard radiation is produced by the XUV spectral energy band which has long been known to have the capability to produce anomalously higher wind ionization stages (e.g., Waldron 1984; MacFarlane et al. 1994; Pauldrach et al. 1994, 2001). Based on solar physics studies, the XUV lower energy bound seems to be rather loosely defined, but the upper limit appears to be fixed at 124 eV (100 Å)\textsuperscript{3} where the XUV upper limit represents the start of the X-ray energy band. For our purposes, we adopt an XUV radiation energy band defined as 54.4 eV (He\textsc{ii} edge) to 124 eV, since below the He\textsc{ii} edge, the radiation is dominated by photospheric emission. Although XUV radiation is un-detectable in O stars, its effects can be manifested by studying other spectral bands. In particular, with regard to the two key arguments used by M03 and F06, we show that XUV radiation produces dissimilar changes in the phosphorous and sulfur ionization equilibria.

2. IMPORTANCE OF XUV RADIATION

In this section, we use graphical arguments to illustrate the importance of XUV radiation with respect to the total radiation cooling curve and the ionization equilibria of phosphorous and sulfur. To emphasize the importance of XUV + X-ray radiation, we provide comparisons with the case when only X-ray radiation is considered. Although unobservable, we believe an observational signature of XUV radiation has already been detected by M03. In their FUSE study of Large Magellanic Cloud (LMC) stars, they explicitly state that “…C\textsuperscript{v} is the dominant species for O stars.” This can only mean that there must be excess XUV emission which the C\textsuperscript{iv} photoionization edge lies within the XUV energy range (see Figure 2).

We first discuss the expected contribution of XUV radiation to the radiative cooling curve (e.g., Cox & Tucker 1969),

\[ \Lambda(T) = \frac{P(T)}{(n_e n_H)} \text{ (erg cm}^3\text{ s}^{-1}) \]

where \( P(T) \) is the power per unit volume, and \( n_e \) and \( n_H \) are the electron and hydrogen number densities, respectively. Although cooling curves have undergone alterations over the years (e.g., atomic data updates and added emission lines), the basic shape of the cooling curve has remained intact as shown in Figure 1. This shows \( \Lambda(T) \) obtained from Raymond & Smith (1977; RS), Mewe et al. (1985; MEKAL), and Smith et al. (2001; APED) data. It also shows that the XUV contribution to \( \Lambda(T) \) is clearly important for temperatures between 0.5 and 2.0 MK.

Since the photoionization edge for P\textsuperscript{v} \( \rightarrow \) P\textsuperscript{vi} is at 65.03 eV, and that for S\textsuperscript{v} \( \rightarrow \) S\textsuperscript{vi} is nearby at 72.68 eV, it seems plausible that their ionization balances should be quite similar. This similarity led to the F06 argument that S\textsuperscript{v} can be used as a surrogate for P\textsuperscript{v}. However, as shown in Figure 2, just beyond the P\textsuperscript{v} photoionization edge there exists a large collection of intense XUV emission lines (their specific contribution is shown in Figure 1) that are located just below the S\textsuperscript{v} ionization energy. Whereas, at energies higher than this edge, the XUV emission at this temperature is essentially devoid of emission lines, i.e., all lines between the S\textsuperscript{v} edge and 124 eV are at least a factor of 100 times smaller than the strongest line just below the S\textsuperscript{v} edge. Consequently, this unique energy distribution of XUV lines relative to the energy locations of these photoionization edges indicates that the XUV emission should produce different effects on the phosphorous and sulfur ionization equilibria. This is illustrated in Figure 3 which shows that the P\textsuperscript{v} photoionization rate is \( \approx \) 10 times larger than the S\textsuperscript{v} rate at the temperature of maximum XUV emission (see Figure 1). Figure 3 includes the C\textsuperscript{iv} rate for comparison, and also shows the expected photoionization rates using only the X-ray energy band (\( \geq 124 \) eV).

As evident from the displacement of these curves, the neglect of XUV radiation leads to underestimates of these rates which are substantial at temperatures \( < \) 2 MK. This implies that alone, the radiation from the X-ray energy band is not expected to have a significant impact on the ionization equilibrium of phosphorous, as was recently demonstrated by Krticka & Kubat (2009) in their study of the Auger effect on the fractional abundance of P\textsuperscript{v}.

Our graphical arguments illustrate that the XUV line emission for temperatures between 0.5 and 2 MK is expected to have a major impact on the ionization structure of phosphorous but a relatively minor effect on sulfur. This implies that the sulfur surrogate argument needs to be re-examined (see Section 3).
The energy-dependent mean intensity (erg cm$^{-2}$ s$^{-1}$ eV$^{-1}$) used to calculate the photoionization rates has two dominant contributions: (1) the photospheric radiation field for a given $T_{\text{eff}}$ and appropriate log $g$ (using the TLUSTY grid of models from OSTAR2002; Lanz & Hubeny 2003), along with the standard geometric dilution factor, and (2) the XUV + X-ray radiation field, $J_X$. This $J_X$ is specified by two parameters, the hot plasma temperature, $T_X$, and the column emission measure, $\Delta EM_X$ (cm$^{-5}$) such that $J_X$($E$, $T_X$) = $\Delta EM_X\epsilon(E, T_X)$ where $\epsilon$ is the energy-dependent emissivity (erg cm$^3$ s$^{-1}$ eV$^{-1}$ str$^{-1}$) taken from the APED data. The basic assumption is that $J_X$ represents an “effective” XUV + X-ray mean intensity at each given radial location, i.e., the wind contains a finite but small level of XUV + X-ray radiation distributed throughout the wind which seems to be supported by observations as discussed in Section 2.

All calculations presented in this section use a $T_{\text{eff}} = 1$ MK, so we can examine the maximal effects of XUV radiation on $q$(P v) and $q$(S v). The total input mean intensity is determined for an energy grid from 8 eV to 2 keV.

Since we are concerned with studying ionization effects for all luminosity classes over a large range in $T_{\text{eff}}$ for which there is P v data, it is advantageous to define a new parameter that is dependent on both X-ray and stellar parameters. By defining $F_X$ as the energy integral of $4\pi J_X$($E$, $T_X$) above the He II edge (erg cm$^{-2}$ s$^{-1}$), then our fundamental adjustable parameter used in this study is defined as $F_X$/$F_*$, where $F_*$ is the total stellar photospheric flux ($L_{\text{bol}}$/4$n_{\text{H}}R_*$)$^2$. Hence, for a given $F_*$, $F_X$/$F_*$, and $T_X$, $\Delta EM_X$ can be extracted directly from

$$\Delta EM_X = \left(\frac{F_X}{F_*}\right)\frac{F_*}{\Lambda(T_X)}.$$  

3. IONIZATION EQUILIBRIUM CALCULATIONS AND REQUIRED XUV RADIATION

The stellar wind ionization equilibria of phosphorous and sulfur are calculated in a straightforward way to determine the level of XUV + X-ray radiation required to affect the fractional ionization abundances, i.e., $q$(P v) and $q$(S v). We consider a stellar effective temperature ($T_{\text{eff}}$) range from 27,500 to 45,000 K which covers the O and early B spectral range where P v has been used to study $M$. The ionization equilibrium is determined by adopting an ionization/recombination rate balance approach similar to the one used in FASTWIND (Puls et al. 2005). The main differences are: (1) we use the photoionization cross sections of Werner & Yakovlev (1995); (2) a wind diffuse field as prescribed by Drew (1989), and (3) we assume a radial power-law-dependent wind temperature ($T_W$) which is adjusted to produce a phosphorous wind ionization structure similar to that of Puls et al. (2008, i.e., no XUV + X-ray radiation) for all $T_{\text{eff}}$ considered. This adjustment leads to a $T_W/T_{\text{eff}} = 1.15(R_*/r)^{0.5}$ with a minimum value of 0.6 $T_{\text{eff}}$. We calculate $q$(P v) and $q$(S v) for wind conditions at a location where the wind velocity is 1/2 the terminal velocity, $v_{\infty}$. For each $T_{\text{eff}}$, a consistent set of stellar parameters (log $g$, $L_{\text{bol}}$, $R_*$) is found by using the fitting formulae given by Martins et al. (2005). We use the electron scattering Eddington factor as described by Lamers (1981) to determine the effective escape velocity, $V_{\text{esc}}$. For the wind parameters, we use $v_{\infty} = 2.6V_{\text{esc}}$ and $M$ predicted by the Vink et al. (2000) formula. The radially dependent wind density is determined from the mass conservation equation using a $\beta$-velocity law $V(r) = v_{\infty}(1 - R_*/r)^{\beta}$ assuming $\beta = 0.8$ (Pauldrach et al. 1986; Müller & Vink 2008). The wind electron density is derived assuming hydrogen and helium are fully ionized.

The dashed-line curves show these rates as determined by using only the X-ray energy band (≥124 eV).

Figure 3. XUV + X-ray photoionization rates for C iv, P v, and S v as a function of temperature assuming that 4$r$ times the total energy integrated XUV + X-ray mean intensity above 54.4 eV is fixed at 10$^8$ erg cm$^{-2}$ s$^{-1}$ for each temperature. The main difference is that the C iv photoionization rate is larger than the P v rate (see Figure 3) due to the differences in their cross sections.

Figure 4. Effects of XUV radiation on $q$(P v) as a function of $T_{\text{eff}}$ for different values of log ($F_X/F_*$) for the three luminosity classes. The black dashed line represents the $F_X = 0$ case. The filled circles are the observationally determined $q$(P v) assuming traditional $M$ from F06 (see Section 3).
where $\Lambda(T_X)$ (erg cm$^3$ s$^{-1}$) is the total energy integral of $4\pi\varepsilon(E, T_X)$ above the He II edge. Note that $F_X/F_*$ is not the same as the well-known observed X-ray to bolometric luminosity ratio, $L_X/L_{Bol}$, because $L_X$ in this ratio is an “observed” quantity, i.e., a measure of only those X-rays capable of escaping the stellar wind, and our $F_X$ is defined as an intrinsic mean intensity where the majority of this emission (i.e., XUV) resides in an observational window that is inaccessible due to wind and interstellar medium (ISM) attenuation.

The predicted $q(P\nu)$ dependence on $F_X/F_*$ for supergiants, giants, and main-sequence stars is shown in Figure 4. Also shown in this figure are the data points from F06 that correspond to the required $q(P\nu)$ values if all stars have their traditional $M$ which we will use to determine the constraints on $F_X/F_*$. This deficit in $q(P\nu)$ relative to unity led F06 to conclude that $M$ needs to be reduced. Figure 4 shows a strong dependence of $q(P\nu)$ on $F_X/F_*$, and indicates that a range in $F_X/F_*$ between $0.3 \times 10^{-7}$ and $10 \times 10^{-7}$ can explain the observed $q(P\nu)$ for all luminosity classes. For example, from Figure 4, the observed $q(P\nu)$ of the four supergiants at $T_{eff} = 35,000$ K indicate a $F_X/F_* \approx 2.5 \times 10^{-7}$. This implies a XUV + X-ray flux $\approx 2 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ and a $\Delta EM_{C} \approx 2.5 \times 10^{39}$ cm$^{-5}$ (using Equation (1)). From X-ray analyses of OB stars, we cannot directly determine $\Delta EM_{C}$, since only the volume emission measure $EM_{V}$ (cm$^{-3}$) can be deduced from observations. If we assume that the XUV + X-ray radiation arises from a spherically shell at the assumed radius ($r = 1.7 R_*$ where $R_0 = 20.5 R_0$), then the “intrinsic” $EM_{V}$ is $\approx 1.8 \times 10^{55}$ (using $4\pi r^2\Delta EM_{C}$) which is comparable to the lowest energy line “observed” $EM_{V}$ ($\approx 5 \times 10^{55}$ for $N vii$) derived from Chandra HETGS observations (e.g., Wojdowski & Schulz 2005). Since the intrinsic $EM_{V}$ is expected to be greater than the observed $EM_{V}$ (optical depth effects), the XUV + X-ray flux required to reduce $q(P\nu)$ is well within the observational limits.

Now we examine the effects of XUV + X-ray radiation on $S\nu$ by considering the ratio $q(P\nu)/q(S\nu)$. As shown in Figure 5, for the case when $F_X = 0$, this ratio is $\approx 1$ for a large range in $T_{eff}$ which supports the F06 $S\nu$ surrogate argument. However, as $F_X/F_*$ increases, $q(P\nu)/q(S\nu)$ decreases which means that $q(S\nu)$ is significantly less sensitive to the XUV + X-ray radiation as compared to the dependence of $q(P\nu)$. This is a direct consequence of the difference in the $P\nu$ and $S\nu$ photoionization rates shown in Figure 3 (see Section 2), and invalidates the sulfur surrogate argument. In general, for all luminosity classes, $q(P\nu)/q(S\nu)$ reaches a minimum value of $\approx 0.14$ over most of the O star spectral range. The required $F_X/F_*$ to produce this minimum value is dependent on luminosity class as shown in Figure 5. These results imply that the $M$ derived from FUSE observations could be underestimated by almost an order of magnitude.

4. DISCUSSION

We have demonstrated that the presence of XUV radiation embedded throughout a stellar wind in sufficient amounts (well within the observational constraints) can lead to a significant depletion of $q(P\nu)$ by using only outer shell photoionization processes. Therefore, the discrepancy between $P\nu$ derived $M$ with those obtained from density-squared diagnostics is far less severe than suggested by F06. Hence, these stars can have $M$ that are again back within a factor of 2 range of the traditional $M$ (consistent with clumped wind predictions). This also means that the XODUR does not require an alternative explanation.

Gudel & Naze (2009) mentioned that there may be a problem with XODUR since the wind opacities used by Waldron & Cassinelli (2007) were determined from a more highly ionized wind. Although it is true that the opacity at low energies can be sensitive to the assumed wind ionization structure, the key point is that the XODUR is based entirely on emission lines at energies $\geq 0.56$ keV where the opacity is almost identical to the “cold” ISM opacity above this energy (e.g., see Figure 2 of Waldron et al. 1998), and the ISM opacity represents the unsurpassable upper limit to any wind opacity. Therefore, regardless of the wind ionization state, the XODUR is certainly valid for those radii derived from the He-like $fir$ lines of Ne ix, Mg xi, Si xii, and S xv, and radii derived from O vii may be marginally dependent on the wind ionization state.

We have shown that the inclusion of XUV radiation can resolve the $M$ discrepancy, and there is observational support that this XUV radiation must be distributed throughout these winds based on the conclusion of M03 regarding $C\nu$. But, what is the source of this emission? Since these winds are clumped, this emission is likely to originate from bow shocks forming around clumps. The Cassinelli et al. (2008) wind bow shock model predicts that the temperature dependence of the emission measure scales as $(T/T_{max})^{-0.7}$, where $T_{max}$ is the temperature at the apex of the bow shock. Hence, there should be a considerable amount of XUV radiation, even for rather strong shocks, located at any radius. Although this XUV radiation is unobservable since essentially all of this radiation will be absorbed by the...
stellar wind and ISM, the strength of this emission can be determined indirectly from analyses of lower energy spectral bands as demonstrated in this Letter.

Future studies now need to focus on alternate explanations as to why the X-ray lines are symmetric and nearly un-shifted. Several possibilities have been proposed: wind porosity effects (Oskinova et al. 2004, 2006); asymmetric mass outflows (Mullan & Waldron 2006), and bow shocks forming around wind clumps (Cassinelli et al. 2008) and stellar ejected plasmoids (Waldron & Cassinelli 2009). In addition, Oskinova et al. (2007) claim that the X-ray line symmetry and P \( P_v \) problems can both be resolved, with no need to reduce \( \dot{M} \), using their planar shock model, porosity effects, and macro-clumping. However, we argue that bow shocks will undoubtedly form around these macro-clumps and the impact of the resultant excess XUV radiation on \( q(P_v) \) needs to be examined. Regardless as to which explanation is applicable, our work has re-emphasized the importance of including the full XUV + X-ray energy spectrum when exploring the effects of radiation on stellar wind ionization structures.

This work was supported by NASA ATFP award NNH09CF39C.

REFERENCES
Abbott, D. C., Bieging, J. H., & Churchwell, E. B. 1981, ApJ, 250, 645
Cassinelli, J. P., Ignace, R., Waldron, W. L., Cho, J., Murphy, N. A., & Lazarian, A. 2008, ApJ, 683, 1052
Cohen, D. H., Leutenegger, M. A., Grizzard, K. T., Reed, C. L., Kramer, R. H., & Owocki, S. P. 2006, MNRAS, 368, 1905
Cox, D. P., & Tucker, W. H. 1969, ApJ, 157, 1157
Drew, J. E. 1989, ApJS, 71, 267
Fullerton, A. W., Massa, D. L., & Prinja, R. K. 2006, ApJ, 637, 1025 (FMP)
Gudel, M., & Nare, Y. 2009, AaAR, 17, 309
Hamann, W.-R., Feldmeier, A., & Oskinova, L. M. (eds.) 2008, Clumping in Hot Star Winds (Potsdam: Univ.-Verl.)
Hirsch, R. 2008, in Clumping in Hot Star Winds, ed. W.-R. Hamann, A. Feldmeier, & L. M. Oskinova (Potsdam: Univ.-Verl.), 9
Kramer, R. H., Cohen, D. H., & Owocki, S. P. 2003, ApJ, 592, 532
Krticka, J., & Kubat, J. 2009, MNRAS, 394, 2065
Lamers, H. J. G. L. M. 1981, ApJ, 245, 593
Lanz, T., & Hubeny, I. 2003, ApJS, 146, 417
MacFarlane, J. J., Cohen, D. H., & Wang, P. 1994, ApJ, 437, 351
Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
Massa, D., Fullerton, A. W., Sonneborn, G., & Hutchings, J. B. 2003, ApJ, 586, 996 (M03)
Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J. 1985, AaAS, 62, 197
Mullan, D. J., & Waldron, W. L. 2006, ApJ, 637, 506
Müller, P. E., & Vink, J. S. 2008, A&A, 492, 493
Oskinova, J., Feldmeier, A., & Hamann, W.-R. 2004, A&A, 422, 675
Oskinova, J., Feldmeier, A., & Hamann, W.-R. 2006, MNRAS, 372, 313
Oskinova, I., Hamann, W.-R., & Feldmeier, A. 2007, A&A, 476, 1331
Owocki, S. P., & Cohen, D. H. 2006, ApJ, 648, 565
Pauldrach, A. W. A., Hoffmann, T. L., & Lennon, M. 2001, A&A, 375, 161
Pauldrach, A. W. A., Kudritzki, R. P., Puls, J., Butler, K., & Hunsinger, J. 1994, A&A, 283, 525
Pauldrach, A. W. A., Puls, J., & Kudritzki, R. P. 1986, A&A, 164, 86
Puls, J., Markova, N., & Scuderi, S. 2008, in ASP Conf. Ser. 288, Mass Loss from Stars and the Evolution of Stellar Cluster, ed. A. de Koter, L. Smith, & L. Waters (San Francisco, CA: ASP), 101
Puls, J., Markova, N., Scuderi, S., Stanghellini, C., Taranova, O. G., Burnley, A. W., & Howarth, I. D. 2006, A&A, 454, 625
Puls, J., et al. 2005, A&A, 435, 669
Raymond, J. C., & Smith, B. W. 1977, ApJS, 35, 419
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91
Verner, D. A., & Yakovlev, D. G. 1995, AaAS, 109, 125
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2000, A&A, 362, 295
Waldron, W. L. 1984, ApJ, 282, 256
Waldron, W. L., & Cassinelli, J. P. 2001, ApJ, 548, L45
Waldron, W. L., & Cassinelli, J. P. 2007, ApJ, 668, 456 (erratum 680, 1595 [2008])
Waldron, W. L., & Cassinelli, J. P. 2009, ApJ, 692, L76
Waldron, W. L., Corcoran, M. F., Drake, S. A., & Smale, A. P. 1998, ApJS, 118, 217
Withbroe, G. L., & Raymond, J. C. 1984, ApJ, 285, 347
Wojdowski, P. S., & Schulz, N. S. 2005, ApJ, 627, 953