QUANTITATIVE X-RAY SPECTRAL MODELING OF THE CANONICAL O SUPERGIANT WIND SHOCK SOURCE ζ PUP: MASS-LOSS RATE AND WIND STRUCTURE

1 Introduction

The archival (AO1) Chandra HETGS spectrum of the O supergiant ζ Pup (68 ks exposure) is one of the richest and most scientifically interesting grating spectra produced in the ten year lifetime of the Great Observatory. The high-resolution, relatively high-signal-to-noise spectrum shows resolved line profiles, whose shapes have been profitably analyzed for the purpose of constraining the standard line-driven instability theory of wind-shock X-ray emission, providing information about the hot plasma's distribution and kinematics. This same line-profile analysis indicates that the mass-loss rate of ζ Pup is a factor of four lower than has been commonly thought. However, large-scale porosity associated with clumping could also play a role, perhaps completely avoiding the need for a downward revision in the star's mass-loss rate.

The controversy over the X-ray line profiles' implications for ζ Pup's - and all OB stars' - mass-loss rates can be addressed by a new, 210 ks HETGS observation. We will use two separate approaches to determine the relative effects of mass-loss rate reduction and porosity: (1) Quantitative analysis of individual emission line profile shapes with models that include porosity, jointly constraining wind optical depths and degree of porosity; and (2) Comparison of the optical depths derived from fitting non-porous models to multiple lines at different wavelengths to see if the trend follows the wavelength-dependence of the atomic opacity.

2 Line profiles, clumping, porosity, and mass-loss rate reduction

The accepted mass-loss rates of O stars have recently come into question, with corrections to density-squared emission diagnostics due to clumping lowering these values by factors of a few. Far-UV measurements of P V (Fullerton) and detailed modeling of UV spectra (Bouret et al.) indicate that mass-loss rates have to be revised downward. If confirmed, this downward revision in O star mass-loss rates would have very significant consequences for stellar evolution, SNe and GRB progenitors, the energetics of the galactic ISM, and for our understanding of these radiation-driven winds themselves. By analyzing X-ray emission line profiles, we have shown (thus far, for ζ Pup and ζ Ori) that the relatively modest asymmetry and blue-shifts provide independent evidence for lower mass-loss rates. In fact, our initial results on ζ Pup (Kramer et al. 2003; Potsdam) show that a factor of four reduction in this star's mass-loss rate is required to explain the X-ray line profiles.

Briefly, the effect of the mass-loss rate on the X-ray profiles comes about because the profile shape is affected by continuum opacity from the cool, X-ray absorbing wind material. Because the red-shifted portion of an X-ray emission line comes from the far side of a spherically symmetric, expanding wind, continuum absorption preferrentially affects it, compared to the blue side of the profile. The overall effect is to shift and skew the profiles in proportion to the optical depth of the wind. Quantitative fitting of the X-ray profiles puts constraints on the optical depth, and if the opacity can be estimated, then the column density, and, ultimately, the mass-loss rate can be determined. This work is one of the major quantitative results of Chandra's legacy for massive stars.

It has been suggested, however, that the effective reduction in optical depth that the existing Chandra HETGS datasets imply could really be evidence not of reduced mass-loss rates but rather of reduced effective opacity due to the porosity associated with large-scale clumping (OFH). Note that the size scale of clumps is unimportant for desnity-squared emission diagnostics, but the effect on X-ray profiles is proportional to the interclump spacing. By fitting quantitative profile models that include the effects of both atomic opacity (OC2001) and

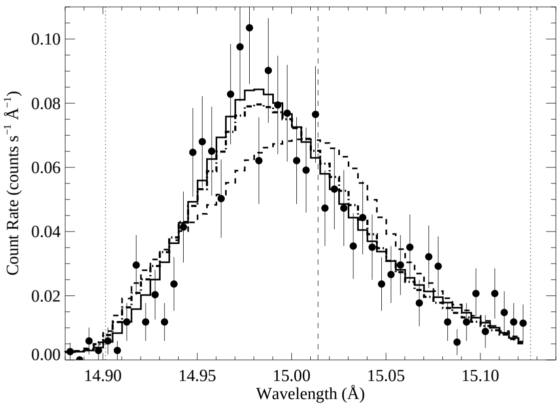

Figure 1: A Fe XVII emission line in the archival Chandra MEG spectrum of ζ Pup, shown along with three models. The vertical lines represent the line's rest wavelength and the Doppler shifts associated with the wind terminal velocity. The solid histogram is the best-fit non-porous model, from which we derive a low optical depth, implying a mass-loss rate four times below the literature value. If we allow for porosity, assuming spherical clumps, then we can fit this line with the higher, literature mass-loss rate, but the best-fit model (dash-dot histogram) requires a large interclump spacing of 3.3 R_* (see Fig. 2). The dashed histogram represents the best-fit porous model with flattened (oblate) clumps instead of spherical ones. Here the interclump spacing is even higher, and the fit is statistically ruled out.

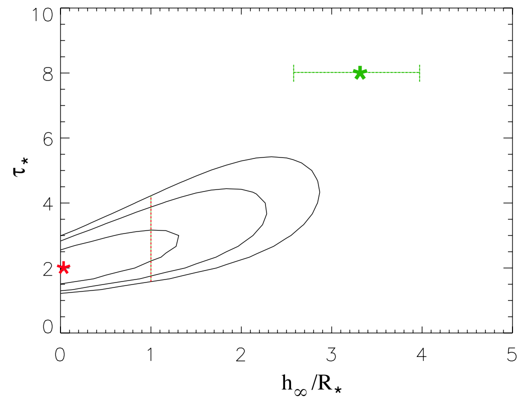

Figure 2: The 68%, 90%, and 95% joint confidence limits on the wind optical depth and the porosity length (interclump spacing) for the fits to the Fe XVII emission line shown in the previous figure. These confidence limits show (a) that the low mass-loss rate model is preferred over the porous model at $>95\%$ confidence, and (b) that porosity lengths, h_∞, of at least 2.5 R_* are required (see the horizontal error bar centered on the best-fit porous model point at $\tau_* = 8$ and $h_\infty = 3.3$). The global best-fit model is indicated by the symbol at $\tau_* = 2$ and $h_\infty = 0$.

porosity (OC2006), we have shown that in order to explain the profiles seen in the Chandra spectrum of ζ Pup, very large (possibly unrealistic) interclump spacings ("porosity lengths," in our parlance) are required (OC2006; Potsdam). In this work, we have also shown that there is a slight statistical preference for reduced mass-loss rates rather than porosity for explaining the detailed profile shapes (see Figs. 1 and 2). Both effects lead to less shifted and more symmetric line profiles, but the specific profile shapes are somewhat different, with porosity leading to profiles that are flatter near line center and have more emission on the extreme blue wings. These differences can be subtle, at least for spherical clumps, but statistical model fitting of data is the only way to quantify the relative effects of mass-loss rate reduction and porosity, and to determine how much porosity is required to mimic a given mass-loss rate reduction.

Formally, the non-porous model is preferred at $\approx 99\%$ level for the Fe XVII line at 15.014 Å in the archival data. However, the porous model fit is not formally bad (it is just not as good as the non-porous model fit). Of course, there are assumptions in the two models, that if relaxed, could easily lead to this statistical difference disappearing. Therefore, we are requesting an additional 210 ks of HETGS data in order to significantly improve the constraints on these two families of line-profile models. Even if no single emission line can be shown to aboslutely rule out all porous models, our quantitative analysis of the ensemble of lines in the HETGS spectrum can put much tighter constraints on the relative ability of porous models vs. lower mass-loss rate models to explain the profiles.

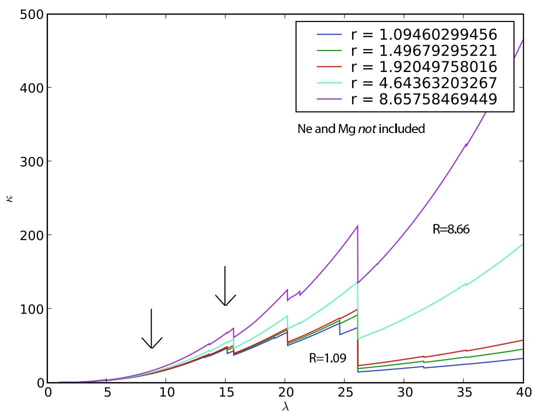

Figure 3: Model of the radius-dependent X-ray opacity in the wind of ζ Pup computed with XCMFGEN. The arrows indicate the wavelengths of the two lines shown in the simulations in Fig. 4.

Another argument employed by the proponents of porosity as the explanation for the profile shapes is that no trend with wavelength from line to line is obvious in the data (OFH2006). This would argue for porosity, as the optically thick clumps that cause a wind to be porous would lead to an effective opacity that is proportional to their physical clump cross section, which will, of course, be independent of wavelength. In contrast, atomic opacity should be rather wavelength dependent. We have argued, however, that the wavelength dependence of the atomic opacity in the spectral region between roughly 10 and 20 Å is grayer than OFH have supposed (Potsdam; and see Fig. 4 in Cohen et al. 1996 and Fig. 2 in Waldron et al. 1998), although it is not absolutely gray. In Fig. 3 we show a detailed model of the wind opacity of ζ Pup, calculated with XCMFGEN, for several different locations in the wind.

Determining whether the optical depth of the strong lines in the HETGS spectrum really is consistent with a single value of optical depth (gray opacity) is critical to evaluating the claims that porosity can explain the X-ray profile shapes. Initial indications are that a single optical depth value can explain morphology of the strongest lines in the spectrum at roughly the 90% confidence level (see Fig 3c in Kramer et al. 2003). Here too, an additional 210 ks of HETGS exposure will likely be able to settle the issue. Our simulations of the proposed combined 210 + 68 ks exposure shows that differences in line optical depth of roughly 50% can be identified via line profile fitting. This is the level of variation expected from realistic models of the wind opacity of ζ Pup over the relevant wavelength range. Specifically, in Fig. 4 we show simulations for two lines that are expected to have optical depths that differ by a factor of two. We have fit these simulated line profile with our empirical wind profile model (OC2001) as implemented in XSPEC. The best-fit values of the fiducial optical depth and their 68% confidence limits are shown on the plots. These simulations show that with the proposed additional 210 ks of data, we will be able to differentiate these two optical depth values at a statistically significant level.

3 Bonus Science

There are at least three other science areas where the new HETGS data is likely to make important contributions: (1) It can address the controversy over the location of the hot, X-ray emitting plasma by providing tighter constraints on the f/i ratio of S XV, which has been claimed to arise very close to the photosphere, as in a corona (Cassinelli et al. 2001; WC07). (2) It will provide the most sensitive test for spectral variability in the X-ray emission from a normal O star. Low-level, periodic ($P = 18^{\rm h}$) variability has been detected in ROSAT observations of ζ Pup (Berghoefer). Is this variability seen in individual spectral features? Can it be attributed to changes in emission or rather to changes in absorption? (3) Finally, resonance scattering has been shown to be affecting the N and O lines in the XMM RGS spectrum of ζ Pup (Leutenegger et al. 2007). The observation we are proposing here will allow us to search for subtler signals of resonance scattering in lines from less abundant elements.

4 Feasibility and Analysis Plan

The beautiful HETGS spectrum of ζ Pup, rich with diagnostics and implications for understanding X-ray emission from hot stars, is one of the major legacies of the Chandra mission. Doubling the signal to noise of the spectrum via the new observation we are proposing here will significantly enhance this legacy. This source is one of the very few for which resolved line profiles provide quantitative diagnostics of key theoretical predictions. Broad spectral lines require a very high quality spectrum if quantitative modeling is to be done profitably, as the counts in each line are spread out over many bins. We have performed simulations using the appropriate response matrices and auxilliary response files, and then performed various model fitting tests of the simulated data. As we have shown, the simulated data from the proposed observation will enable us to differentiate wind optical depth variations from line to line of less than a factor of two, as well as provide tighter constraints on the trade-off between porosity and atomic opacity when we analyze individual lines. In terms of the f/i diagnostics, increasing the total counts in the S XV complex, for example, to more than 300 will enable us to put some meaningful constraints on the location of the hottest plasma on this O star ($f/i = 0.6$ and 2.0 can be distinguished at $> 95\%$ confidence ($\Delta C = 5$) in S XV). Because high spectral resolution is required for much of the science we are proposing, and because the shortest wavelength lines, which are subject to relatively little wind absorption, are crucial for this science, Chandra, rather than XMM, is the ideal instrument to carry out these observations.

Our research team has extensive experience in X-ray spectral analysis, including quantitative statistical fitting of high-resolution Chandra spectra. We have also developed empirical models of wind-shock X-ray emission and line profiles, as well as performing numerical simulations of OB star winds. Zsargo and Hillier have extensive experience in detailed atomic and spectral modeling of extended atmospheres, including the effects of X-rays on the bulk, clumped winds of O stars. The detailed wind opacity models that they will make for ζ Pup will be key in our physical interpretations of the new X-ray spectrum.

5 References

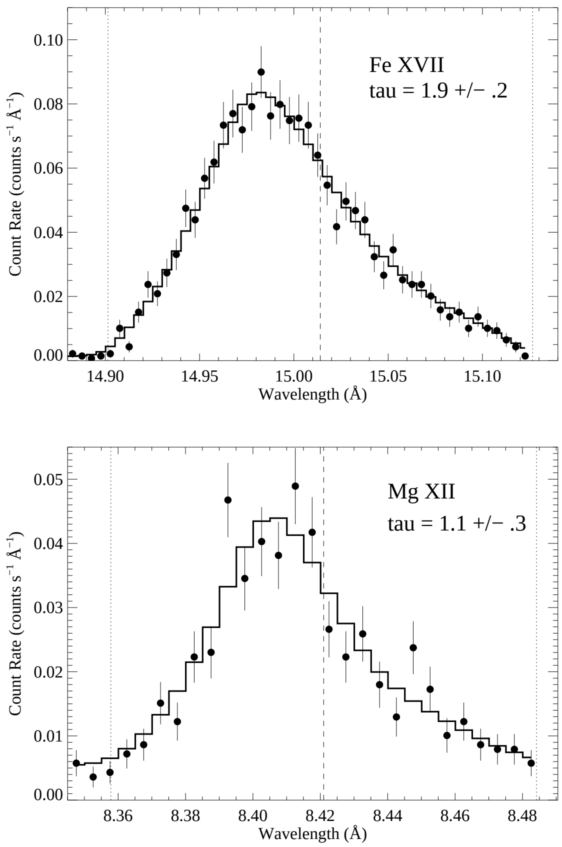

Figure 4: Simulated data for the Fe XVII line at 15.014 Å (top; compare to Fig. 1) and Mg XII Ly-alpha at 8.421 Å (bottom). The simulations assumed a fiducial wind optical depth of $\tau_* = 2$ for the Fe XVII line and $\tau_* = 1$ for the Mg XII line (note the larger shift and asymmetry in the higher τ_* line). When we fit these simulated data with our wind profile model, we derive optical depths of $\tau_* = 1.9 \pm 0.2$ and $\tau_* = 1.1 \pm 0.3$, respectively. Thus the proposed 210 ks exposure will enable us to determine if the wind opacity truly is gray, as would be expected in a porosity-dominated wind. If the expected wavelength dependence is instead seen, as in these simulations, then a significant mass-loss rate reduction would be the favored interpretation.