QUANTITATIVE X-RAY SPECTRAL MODELING OF THE CANONICAL O SUPERGIANT WIND SHOCK SOURCE ζ PUP

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. And as an unexpected benefit of this quantitative line profile analysis, it has been shown that the mass-loss rate of this star has likely been overestimated by a factor of four. Additionally, the forbidden-to-intercombination line ratios of several helium-like ions have been used to place quantitative constraints on the spatial distribution of the hot plasma, which have provided key information about the characteristics, and even the applicability, of the wind-shock mechanism.

There are several open questions and controversies regarding the interpretation of the X-ray emission from ζ Pup involving the wind-shock mechanism, the constraints on the spatial and velocity distribution of the shock-heated plasma, and, crucially, about the implications for this star's - and all OB stars' - mass-loss rates. A new, 210 ks long HETGS observation can answer the following questions: (1) Must the mass-loss rate estimate be revised significantly downward or could large-scale wind clumping explain the surprisingly symmetric line-profile shapes? And (2) is there any solid evidence for hot plasma so close to the photosphere that the standard wind-shock scenario cannot explain the data and some type of coronal mechanism needs to be invoked? A new, long grating observation may also enable us to answer additional questions of interest to the community, including: Is there evidence for resonance scattering in strong lines (as has been hinted at in the higher S/N but lower resolution RGS data)? Is there any evidence for spectral time-variability in wind-shock X-ray sources? Is there any evidence at all for narrow radiative recombination continua that are the hallmark of the cold electron population predicted by a radical new theory of non-equilibrium shock emission that has been put forward to explain the X-rays from single O stars?

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. Similarly, although f/i line ratio diagnostics have been employed for many objects, this is one of the few where quantitative analysis of this diagnostic provides significant discriminatory power with respect to specific, conflicting model predictions. Our research team, with its interest and expertise in the application of these quantitative diagnostics, statistical analysis, and theoretical modeling is uniquely qualified to analyze this spectrum and address the open questions in O star X-ray production and wind properties.

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 indicate that mass-loss rates have to be revised downward (Bouret). 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 (Potsdam) show that a factor of 4 reduction in this star's mass-loss rate is required to explain the X-ray line profiles. This is in very good agreement with recent detailed UV spectral modeling of this star (Bouret, Kauai poster).

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). By fitting quantitative profile models that include the effects of both atomic opacity and porosity (see Fig. 1), 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 Fig. 2). These two effects both 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

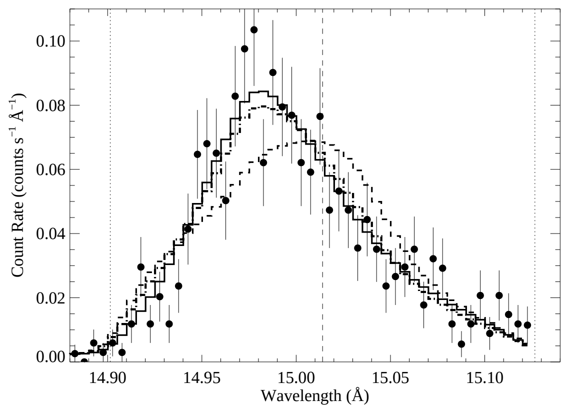

Figure 1: A Fe XVII emission line in the archival Chandra MEG spectrum of ζ Pup, shown along with three models. The solid histogram is the best-fit non-porous model, from which we derive a low optical depth, implying a mass-loss rate four times below the literature value. If we allow for porosity, assuming spherical clumps, then we can fit this line with the higher, literature mass-loss rate, but the best-fit model (dash-dot line) requires a large interclump spacing of 3.3 R_*. The dashed line 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.

more emission on the extreme blue wings. These differences can be subtle, at least for spherical clumps, but statistical fitting of models 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. 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

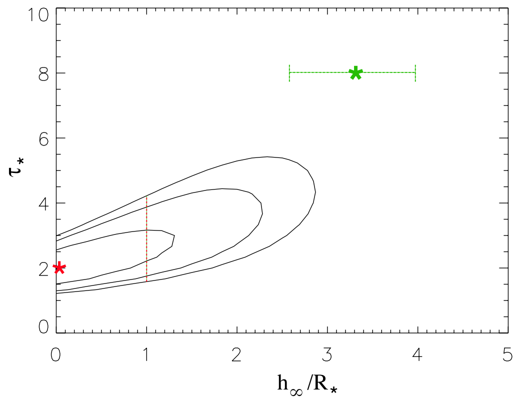

Figure 2: The 68%, 90%, and 95% joint confidence limits on the wind optical depth and the porosity length (interclump spacing) for the fits to the Fe XVII emission line shown in the previous figure. These confidence limits show (a) that the low mass-loss rate model is preferred over the porous model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

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

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. Therefore, determining whether the optical depth of the strong lines in the HETGS spectrum really is consistent with a single value 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 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.

3 Helium-like f/i line ratios and wind-shock vs. coronal emission models

In OB stars, the forbidden-to-intercombination line ratios of helium-like ions are sensitive to the local UV radiation field mean intensity, and thus to the distance from the photosphere (if the photospheric emergent flux at the relevant wavelength is known). This diagnostic has proved to be very useful in differentiating coronal models (X-ray emitting plasma right near the photosphere) from wind shock models (X-ray emitting plasma well above the photosphere). For lower Z elements (typically Ne IX, Mg XI, and Si XIII) the results are conclusive: the hot plasma is distributed in the wind, well above the photosphere, as is expected in the wind shock scenario. It has been suggested, however, that for higher Z elements (from hotter plasma, with $T > 10^7$ K) there is evidence from low f/i ratios that the plasma is near the photosphere, as is expected in the coronal scenario (and inconsistent with wind-shock models). A hybrid wind-coronal model has been proposed to explain both the lower and higher Z complexes (Mullan & Waldron, 2006).

However, the conclusions from the high Z complexes, which tend to have quite low S/N in the archival Chandra data for O stars, are controversial. Leutenegger et al. (2006) and Leutenegger

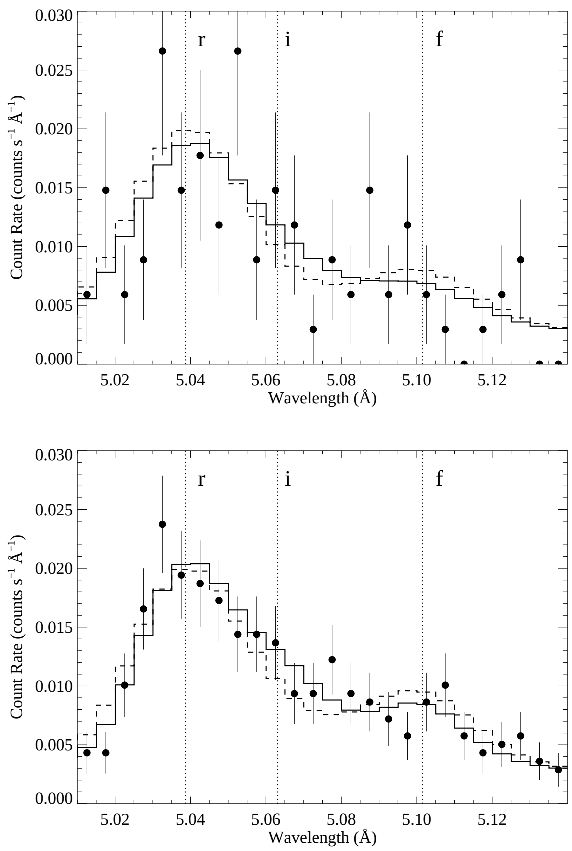

Figure 3: The S XV complex in the archival 68 ks MEG exposure of ζ Pup, with two models superimposed (top). The rest wavelengths of the resonance (r), intercombination (i), and forbidden (f) lines are indicated by the vertical dotted lines. The solid histogram is the model found by Cassinelli et al. (2001) to imply plasma very close to the photosphere; it has $f/i = 0.61$, while the dashed histogram has $f/i = 2.0$, which implies no upper limit on the distance of the plasma from the photosphere. Using standard statistical analysis procedures, these two models can be differentiated at only the 68% level ($\Delta C = 1$). The bottom panel shows a simulated spectrum, based on our proposed new 210 ks exposure added to the 68 ks exposure, of the same complex. The simulation assumes the value found by Cassinelli et al. (2001) of $f/i = 0.61$. In this case, when we fit the simulated data, the 90% upper limit on f/i is just 1.29, and the value of $f/i = 2.0$ (dotted histogram) is ruled out at more than the 95% confidence limit ($\Delta C \approx 5$). Bear in mind that although the difference between the two models is smaller than the typical data error bars, when using the C statistic on unbinned data, smaller differences can be distinguished.

(2008) have argued that the data are not of sufficient S/N to place any meaningful constraints on the plasma location for the high Z complexes. The S XV complex in the HETGS spectrum of zeta Pup is a key piece of data in this controversy (note that this complex has only 85 MEG counts in the archival 68 ks dataset). Cassinelli et al. (2001) argued that the location of the helium-like S XV must be within a few tenths of a stellar radius of the star's photosphere, thus posing a very serious challenge to the wind shock scenario that seems to explain much of the rest of the X-ray data for this star. Standard statistical analysis techniques show that the 68 ks archival observation cannot place meaninful constraints on the location of the X-ray emitting plasma (see Fig. 3, top panel).

Doubling the signal to noise ratio of the HETGS spectrum of ζ Pup, as we are proposing here, will enable us to definitively determine whether the hottest plasma on this O supergiant is being produced by wind shocks (Fig. 3, lower panel; models differentiated with $> 95\%$ confidence). If so, it would, along with the line profile analysis we have described above, provide a complete and unified picture of X-ray emission from shocks in a lower opacity, possibly significantly clumped, stellar wind. If not, then a somewhat radical - and very interesting - picture of a hybrid wind/coronal mechanism might need to be invoked.

4 References