Quantifying the trade-offs between mass-loss rate reduction and porosity via the *Chandra* HETGS emission line profiles of ζ Puppis

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ABSTRACT

We explore the joint effects of mass-loss rate reduction and isotropic porosity on symmetrizing x-ray emission line profiles, using the high signal-to-noise *Chandra* grating spectrum of ζ Puppis as a test case.

1. Introduction

Note that although this document is formatted as a manuscript, at this point, it is more in the spirit of a memo to be circulated among collaborators.

The recent papers describing the effects of porosity on x-ray line profiles suggest that porosity's symmetrizing effects can explain (Oskinova, Feldmeier, & Hamann 2006) what previously had been interpreted as reduced continuum opacity (and, ultimately, attributed to reduced mass-loss rates)...or that it really *cannot* explain the surprisingly mild asymmetries and blue-shifts seen on the x-ray emission lines of O stars unless unrealistically large values of the porosity length are invoked (Owocki & Cohen 2006).

Here we report on fits we performed to the Fe XVII emission line at $\lambda = 15.014$ Å in the *Chandra* HETGS spectrum of ζ Pup(MEG $m = +/-1$ orders). The HEG spectrum has negligible flux in this line. This line is representative - Kramer, Cohen, & Owocki (2003) fit it with a pure Owocki & Cohen (2001) line profile model having a best-fit $\tau_* = 1.0$. Our goals are to determine the extent to which opacity effects and porosity effects can be differentiated with real data. And to the extent they can be differentiated, which is preferred; which provides a better fit to the data. Even if the two effects cannot be differentiated, fitting real data will allow us to explore the trade-offs, or joint constraints, between opacity (via τ_*)

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and porosity (via h_∞). Specifically, we can answer the question, what values of the porosity length are required to fit the data, assuming that the literature mass-loss rates are correct?

2. The model and the fits

The line-profile model we use is the standard Owocki & Cohen (2001) four-parameter model (q, τ_*, $u_{\rm max}({\rm R}_*/{\rm R}_{\rm min})$, and normalization), modified for the effects of isotropic porosity, using the effective opacity treatment of Owocki & Cohen (2006), according to eq. (11) in that paper. However, rather than assuming that the porosity length is proportional to the local radius, as $h = h'r/{\rm R}_*$, we assume that the clumps follow the wind velocity law (taken to be $\beta = 1$). The local value of the porosity length thus scales as $h = h_\infty(1 - {\rm R}_*/{\rm r})$ (should reference Stan's notes here). The porosity model is implemented in XSPEC in Maurice's early-April version of *windprof* (note that *windprof* can include either the h' option or the h_∞ option). We include a continuum component under the line in all of our modeling.

The data we fit is the first-order MEG only, over the interval $14.85 < \lambda < 15.13$, which comprises 110 bins. We use the C-statistic to evaluate goodness of fit and to quantify the confidence limits on the fitted parameters.

The first fit we performed was the most general: all five parameters (q, τ_*, $u_{\rm max}$, normalization, and h_∞) were free to vary, as was the normalization of the continuum. The best-fit model parameters are in good agreement with the results of Kramer, Cohen, & Owocki (2003), including $\tau_* = 1.12$, and has the best-fit terminal porosity length value of $h_\infty = 0.00$. The best-fit parameters are summarized in Table 1. The best-fit model is shown, superimposed on the data in Fig. 1. The fit is very good. In fact, the very low C statistic value implies a rejection probability of only 3%. This is determined from fitting an ensemble of Monte Carlo simulated datasets and comparing the C statistic from the fit to the data to the distribution of C statistics generated from the Monte Carlo simulations.

We should think about what it means that the fit is formally so good. We could say that the model is more detailed or complext than it needs to be. We could eliminate one or more of the free parameters. But we really have no *a priori* way to decide which ones are reasonable to eliminate (and what values we'd fix them at). In fact, if we were to eliminate one parameter, I would say the most reasonable thing would be to neglect porosity, functionally setting $h_\infty = 0$. But this is the best-fit value in any case.

Given this best-fit model, we can quantify the uncertainties on the derived model parameters via the usual "ΔC statistic" method. This will allow us to see how much larger than zero h_∞ can be before the model fit is significantly worse than the best-fit model. It will also enable us to see how much higher the derived τ_* value can be. We show the joint constraints on τ_* and h_∞ in Fig. 2. It can be seen from this figure that at the 90% confidence level, h_∞can be almost as large as 3. But interestingly, even if h_∞ is this large, τ_* does not have to increase by very much.

I am actually somewhat surprised by this, as $h_\infty \approx 3$ seems like it should have a pretty big effect. Maybe this is the difference between h' and h_∞, and perhaps this difference is accentuated when τ_* is not very big. Because then the densest parts of the optically thin region is relatively close to the photosphere and thus $v < v_\infty$ and $h < h_\infty$. We can look at a model that is within the 90% confidence region but has relatively large values of τ_* and h_∞. We show such a model in Fig. 3, with the corresponding fit parameters listed in Table 2. This fit, to my eye, looks perhaps a little worse than the best fit, but it still looks good. And indeed, as measured by Monte Carlo simulations of this model, the rejection probability is just as low.

Next, we look at a model with a high τ_* value; something consistent with the literature mass-loss rate. Without a specific, detailed calculation of the x-ray opacity of the wind, we are guided previously published opacities and related quatities for this and other stars' winds. The expected wind optical depth under the assumption of a smooth wind is about an order of magnitude than the values found from fitting the Owocki & Cohen (2001) model to data, so we will choose $\tau_* = 15$ as the value expected for a smooth wind and literature mass-loss rate.

In Fig. 4 we show the best-fit model with τ_* fixed at 15, and all the other parameters free. The best fit model has $h_\infty = 5.5$. The lower limit on h_∞ is 4.5. So, a rather large value of the porosity length is required if the mass-loss rate is not reduced. The model parameters of this fit are summarized in Table 3. Note that $R_{\rm min}$ did not change very much, but q did. The best-fit value is $q == 0.82$. This high q value will de-emphasize the wings of the line. Note that a bump or flatening out of the profile can be seen near line center in this model. The model systematically overpredicts the flux in this part of the profile. It should be noted that the C statistic (like the chi-square statistic) is unaffected by correlations in the deviations; by long runs of bins that all either over- or under-predict the level seen in the data. Some rank-order statistic might be more sensitive in this regard.

Finally, note that this model is significantly worse than the best-fit model shown in Fig. 1 – the C statistic is 98 compared to 86. However, because the quality of the best fit is so good, the significantly worse fit still have a reasonable goodness of fit. So, in what sense can we rule out this high-τ_*, high-h_∞ model? I think we can only say that the low-τ_*, low-h_∞ model is preferred.

3. Discussion

4. Conclusions

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Table 1. Fitted parameters for the best global model – all parameters free

parameter	value
q	-0.02
τ_*	$1.12^{+1.28}_{-0.32}$
h_∞	$0.00^{+2.8}_{-0.0}$
$R_{\rm min}$	1.53
C	82.95
rej. prob.	3%

Table 2. Parameters for a model with $\tau_* = 2$, $h_\infty = 2$ – all other parameters free

parameter	value
q	-0.04
τ_*	2
h_∞	2
$R_{\rm min}$	1.56
C	86.19
rej. prob.	3%

Table 3. Parameters for a model with $\tau_* = 15$ – all other parameters, including h_∞, free

parameter	value
q	0.82
τ_*	15
h_∞	$5.5^{+1.2}_{-1.0}$
$R_{\rm min}$	1.73
C	98.44
rej. prob.	10%

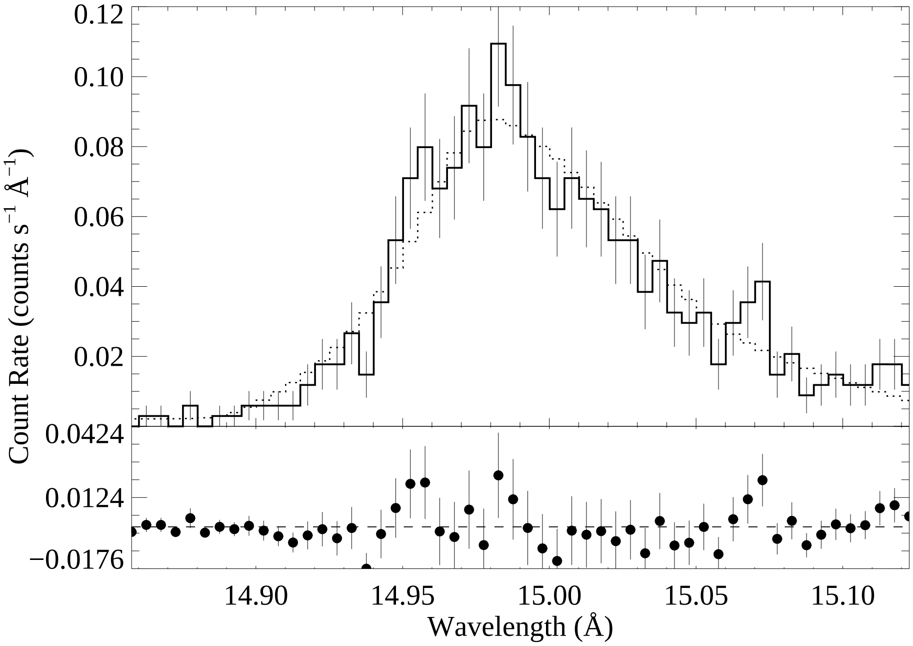

Fig. 1.— The global best-fit wind profile model for the Fe XVII line ($\lambda_{\rm lab}$ = 15.014 Å) measured in the MEG first order (negative and positive orders co-added). In this model, the free parameters were q, $u_{\rm max}$, τ_*, h_∞, and the normalization of the line profile, as well as the normalization of the power-law continuum model (for which we fixed the power-law index at $\alpha = 2$). The fit is formally very good. (fexvii_1501_windprof_best_q_thawed.ps)

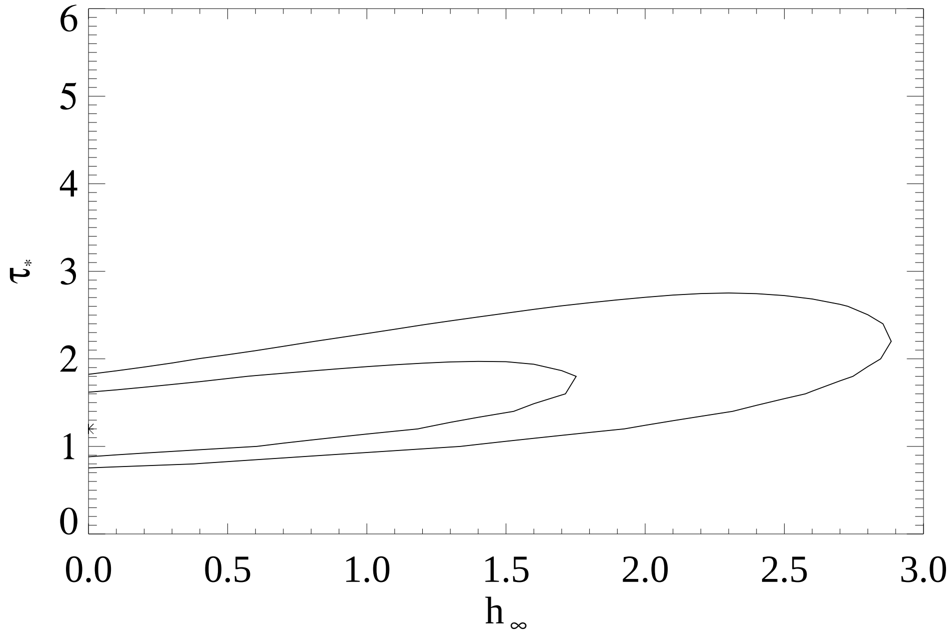

Fig. 2.— The 68% and 90% confidence regions for two parameters of interest ($\Delta C = 2.3$, 4.61). The calculated grid is 20 by 20, and for each of the 400 models, the other parameters (q, $u_{\rm max}$, normalization, and the normalization of the power-law continuum) were free to vary until a best-fit model for those values of τ_* and h_∞ was found. The best-fit value on the grid is indicated with an asterisk. (fexvii_1501_thawed_q.ps)

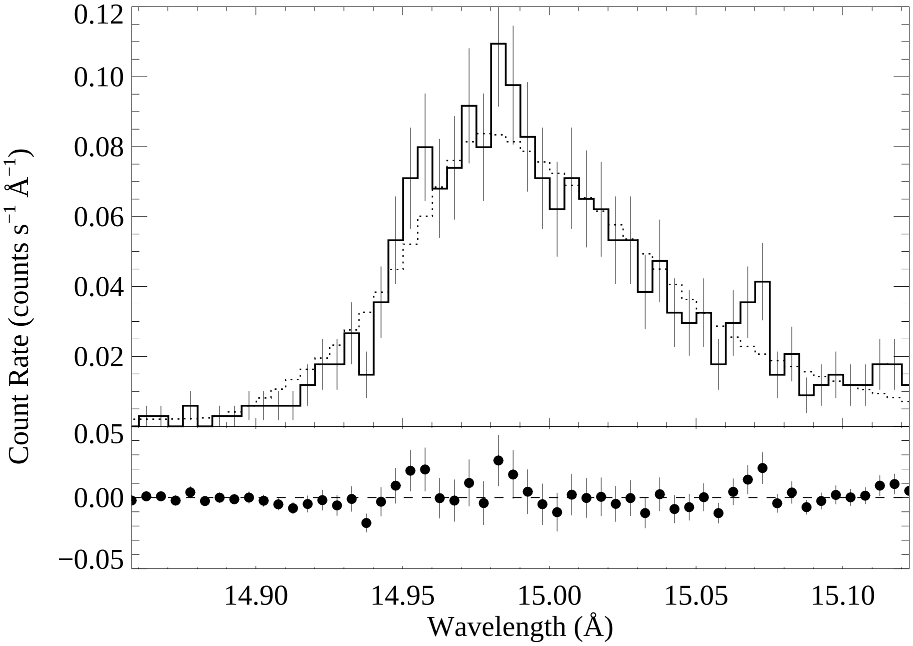

Fig. 3.— This fit has two additional parameters fixed, and represents a marginally acceptable fit, as compared to the best-fit model. (fexvii_1501_windprof_moderate_q_thawed.ps)

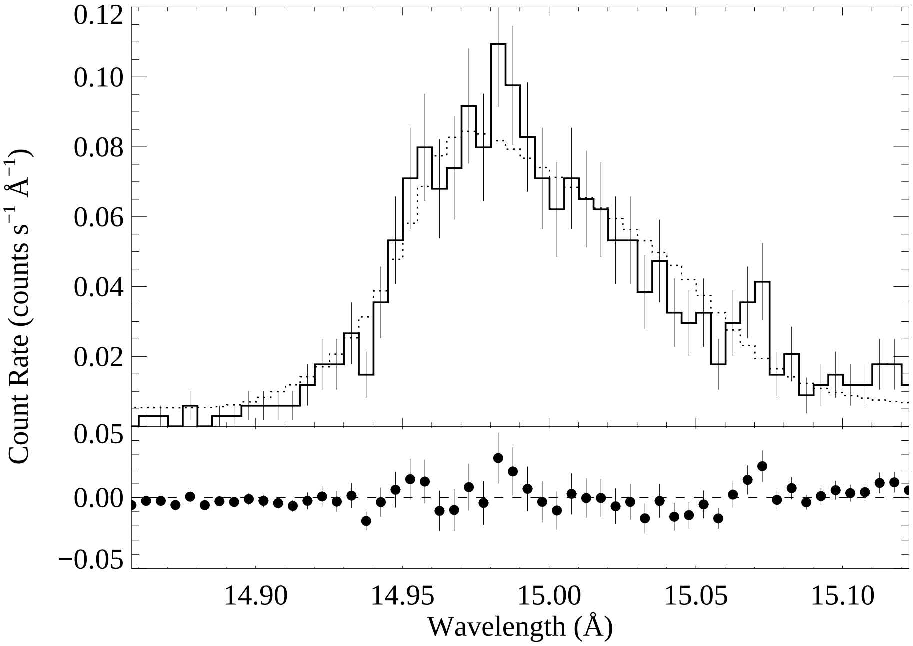

Fig. 4.— This fit has τ_* fixed at 15, with all the other parameters being free. The fit is significantly worse than the best-fit model shown in Fig. 1. (fexvii_1501_windprof_best_tau_15.ps)