Clumping in Hot Star Winds
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Resonance scattering in the X-ray emission lines profiles of ζ Puppis

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We present XMM-*Newton* Reflection Grating Spectrometer observations of pairs of X-ray emission line profiles from the O star ζ Pup that originate from the same He-like ion. The two profiles in each pair have different shapes and cannot both be consistently fit by models assuming the same wind parameters. We show that the differences in profile shape can be accounted for in a model including the effects of resonance scattering, which affects the resonance line in the pair but not the intercombination line. This implies that resonance scattering is also important in single resonance lines, where its effect is difficult to distinguish from a low effective continuum optical depth in the wind. Thus, resonance scattering may help reconcile X-ray line profile shapes with literature mass-loss rates.

1 Introduction

Recent studies of X-ray emission line Doppler profiles from O stars have found that the profiles are too symmetric to be explained in the context of a smooth-wind model, assuming the published mass-loss rates of O stars are correct (e.g. Kramer et al. 2003, Cohen et al. 2006).

There is mounting evidence from studies of UV absorption profiles as well as other lines of inquiry that the true mass-loss rates of O stars are at least a factor of a few smaller than those derived from density-squared diagnostics (e.g. Bouret et al. 2005, Fullerton et al. 2006). However, some of the observed X-ray profiles appear to require mass-loss rate reductions of an order of magnitude (e.g. Kramer et al. 2003, Cohen et al. 2006).

Two alternative explanations for X-ray profile shapes may mitigate the requirement for large mass-loss rate reductions. *Porosity*, the formation of very large, optically thick clumps, could reduce the effective opacity of the wind to X-rays (e.g. Oskinova et al. 2006, Owocki & Cohen 2006). *Resonance Scattering* could change the local angular distribution of emitted X-rays, symmetrizing line profiles and mimicking the symmetric profiles of a wind with little absorption (Ignace & Gayley 2002).

2 He-like emisison line profile discrepancy

In Leutenegger et al. (2007) we present over 400 ks of net XMM-*Newton* Reflection Grating Spectrometer (RGS) data from observations of ζ Pup. This is by far the highest signal-to-noise high-resolution X-ray spectrum available for any O star. In figures 1 and 2 we show this data with the line profile models for the N VI and O VII He-like triplets of ζ Pup, respectively. The profile model is described in Owocki & Cohen (2001) and Leutenegger et al. (2006). Because of photoexcitation of the metastable 1s2s $^3S_1$ state, there are effectively only two lines in each triplet, resonance (r) and intercombination (i). Note however that the models *do* correctly account for the radial dependence of the forbidden-to-intercombination line ratio, as described in Leutenegger et al. (2006). This can be seen in the weak, broad forbidden lines (f).

The models shown have been chosen to fit the red wing of the intercombination line in order to show that the model resonance line is obviously too blueshifted for both complexes. The best-fit models, presented in Leutenegger et al. (2007), have strong residuals in both lines. In both cases, the model clearly does not fit the data, and the r and i lines clearly have different shapes. The observed difference in the profile shapes is an empirical fact, and it is independent of modelling assumptions.

This is remarkable, because we expect these lines to have almost the same profile (modulo the small difference caused by the changing forbidden-to-intercombination line ratio at large radii). This is because both of these lines originate from transitions in the *same ion*.

Resonance scattering can symmetrize lines with high optical depths. The difference in observed profile shapes suggests that this effect is responsible for the shape of the resonance line, which has a high oscillator strength, while it does not affect the intercombination line, which has a low oscillator strength.

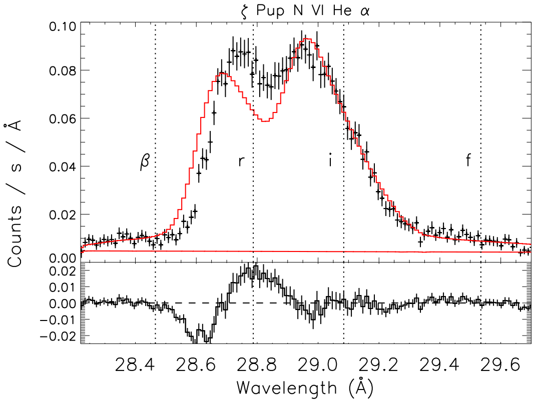

Figure 1: N VI He-like triplet from ζ Pup observed with RGS. The model (red line) does not include resonance scattering and is chosen to fit the red wing of the intercombination line. The dashed lines labelled r, i, f, and β indicate the rest wavelengths of the resonance, intercombination, and forbidden lines, and the C VI Lyβ line, respectively. The lower red line gives the continuum strength.

3 Profiles including resonance scattering

The theory of resonance scattering in O star X-ray line profiles is discussed in Ignace & Gayley (2002) and Leutenegger et al. (2007). In both these analyses, radiative transfer is considered in the Sobolev approximation.

One of the main results of Sobolev theory is that the optical depth of a strong line at a given point depends on the local line-of-sight velocity gradient. In a spherically symmetric radial outflow, the velocity gradient in the radial direction is just the velocity gradient of the flow, dv/dr. In the lateral direction, the line-of-sight velocity gradient is a consequence of the spherical divergence of the wind, v/r.

For a wind with a $\beta = 1$ velocity law, $v/r > dv/dr$ beyond two stellar radii. Far out in the wind, the radial velocity gradient is negligible. Photons emitted primarily from far out in the wind thus see a much higher optical depth in the radial direction than in the lateral direction, and they escape preferentially in the lateral direction. Since the projected velocity is the product of the outflow velocity times the direction cosine, profiles formed by photons emitted preferentially in the lateral direction will be more symmetric than profiles resulting from isotropic emission. This will be the case in typical X-ray line profiles, as long as the continuum optical depth is high enough to obscure photons coming from the inner part of the wind.

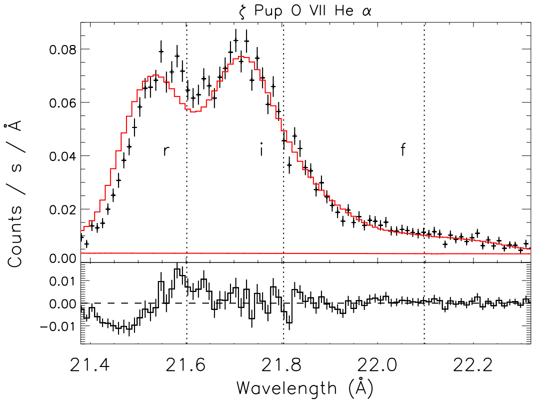

Figure 2: Same as Fig. 1, but for O VII.

In Leutenegger et al. (2007), we introduce a new free parameter, $\tau_{0,*}$, which gives the characteristic Sobolev optical depth for a given line. In Figure 3 we plot model profiles with different values of $\tau_{0,*}$. The models all have the same parameters, other than the variation of the characteristic line optical depth. The effect of resonance scattering is to significantly symmetrize a line profile, with higher optical depths causing stronger symmetrization. For a more in depth discussion of the derivation of this model and its parameters, see Leutenegger et al. (2007).

4 Application of resonance scattering models to data

In figures 4 and 5 we show the best fit models for N VI and O VII including the effects of resonance scattering. These models obviously fit the data much better than the models without resonance scattering. The fact that we observe the same effect in two different ions suggests that this is not a spectroscopic artifact or anomaly. The O VII complex requires a moderate line optical depth, while the N VI complex requires a high line optical depth.

5 Conclusions

By comparing the shapes of line profiles from resonance and intercombination lines originating from the same He-like ion in the X-ray spectrum of ζ Pup, we find that resonance scattering is important in the formation of the resonance lines and causes them to be significantly more symmetric than the intercombination lines.

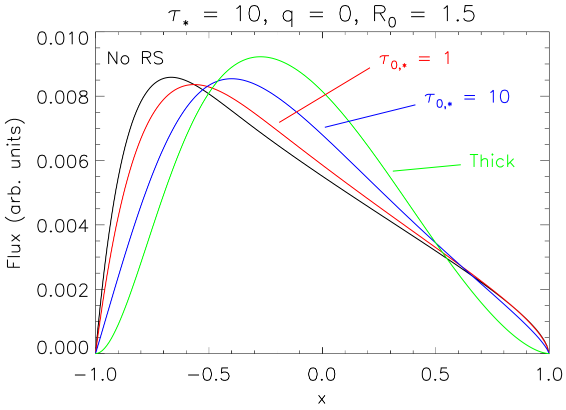

Figure 3: Comparison of different values of the characteristic line optical depth $\tau_{0,*}$.

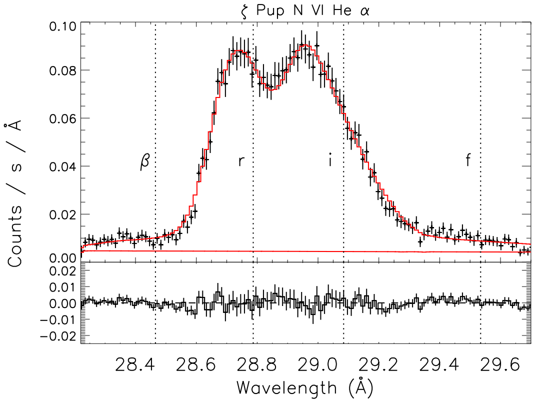

Figure 4: As Fig. 1, but showing the best fit model including resonance scattering for N VI.

This effect could be important for many lines in O stars with high mass-loss rates, and any future analyses of line profiles should take it into account. However, we expect that this effect will be more marginal for K-shell lines of Ne and higher Z elements and L-shell lines of Fe due to their lower elemental abundances.

Accounting for this effect in modelling will allow a partial reconciliation with published mass-loss rates based on density-squared diagnostics, but will likely still require reductions in O star mass-loss rates of a factor of a few. We estimate that our measured values of the continuum optical depth τ_* are consistent with a mass-loss rate of $\sim 1.5 \times 10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$, which is a factor of a few greater than the mass-loss rate suggested by modeling profiles without including the effect of resonance scattering. Furthermore, we also estimate that our values of τ_* are consistent with those inferred from the fits to the 15.014 Å line of Fe XVII and the Lyα line of Ne X in the *Chandra* HETG spectrum of ζ Pup presented by Cohen et al. in these proceedings.

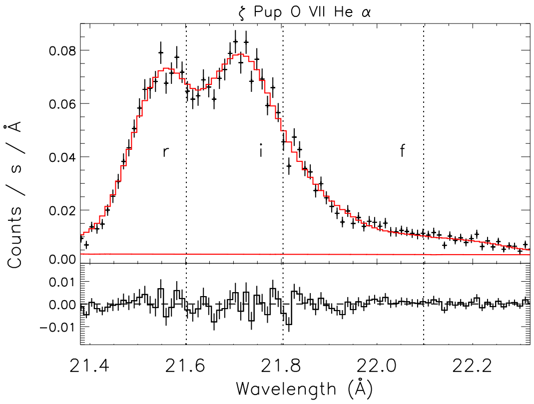

Figure 5: As Fig. 4, but for O VII.

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