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Wind signatures in the X-ray emission-line profiles of the late-O supergiant ζ Orionis

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ABSTRACT

X-ray line-profile analysis has proved to be the most direct diagnostic of the kinematics and spatial distribution of the very hot plasma around O stars. The Doppler-broadened line profiles provide information about the velocity distribution of the hot plasma, while the wavelength-dependent attenuation across a line profile provides information about the absorption to the hot plasma, thus providing a strong constraint on its physical location. In this paper, we apply several analysis techniques to the emission lines in the *Chandra* High Energy Transmission Grating Spectrometer (HETGS) spectrum of the late-O supergiant ζ Ori (O9.7 Ib), including the fitting of a simple line-profile model. We show that there is distinct evidence for blueshifts and profile asymmetry, as well as broadening in the X-ray emission lines of ζ Ori. These are the observational hallmarks of a wind-shock X-ray source, and the results for ζ Ori are very similar to those for the earlier O star, ζ Pup, which we have previously shown to be well fit by the same wind-shock line-profile model. The more subtle effects on the line-profile morphologies in ζ Ori, as compared to ζ Pup, are consistent with the somewhat lower density wind in this later O supergiant. In both stars, the wind optical depths required to explain the mildly asymmetric X-ray line profiles imply reductions in the effective opacity of nearly an order of magnitude, which may be explained by some combination of mass-loss rate reduction and large-scale clumping, with its associated porosity-based effects on radiation transfer. In the context of the recent reanalysis of the helium-like line intensity ratios in both ζ Ori and ζ Pup, and also in light of recent work questioning the published mass-loss rates in OB stars, these new results indicate that the X-ray emission from ζ Ori can be understood within the framework of the standard wind-shock scenario for hot stars.

Key words: line: profiles – stars: early-type – stars: individual: ζ Ori – stars: mass-loss – stars: winds, outflows – X-rays: stars.

1 INTRODUCTION

X-ray emission from normal, single OB stars has generally been explained in terms of shock heating of the massive, highly supersonic, radiation-driven winds of these very luminous stars (Pallavicini et al. 1981; Corcoran et al. 1993; Hillier et al. 1993; Cassinelli et al. 1994; Drew, Hoare & Denby 1994; Cohen et al. 1996; Kudritzki et al. 1996; Owocki & Cohen 1999). The standard model involves the line-force instability, initially noted in the context of hot-star winds by Lucy & Solomon (1970) and later investigated by Lucy & White (1980),

Lucy (1982), Owocki & Rybicki (1984), Owocki, Castor & Rybicki (1988), Feldmeier et al. (1997a), Feldmeier, Puls & Pauldrach (1997b) and Runacres & Owocki (2002). The wind-shock X-rays in this scenario arise naturally from non-local radiation transfer in the context of the standard ‘Castor, Abbott and Klein (CAK)’ line-driven winds of massive stars (Castor, Abbott & Klein 1975).

Other wind-shock models of X-ray production have also been proposed, based on corotating interaction regions (Mullan 1984), driven shocks (MacFarlane & Cassinelli 1989) and inverse Compton scattering (Chen & White 1991). Even in the context of the line-force instability mechanism, there are different scenarios based on the self-excited instability (Owocki et al. 1988) versus the instability seeded by perturbations at the base of the wind (Feldmeier et al.

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1997b), and one-dimensional simulations versus two-dimensional simulations (Dessart & Owocki 2003).

Despite this proliferation of models, very few observational constraints could be put on any of these wind-shock models until recently. This was at least partly because of the very limited data quality of X-ray observations before the late 1990s. Furthermore, the idea that dynamo-driven coronal mechanisms, similar to what is seen on the Sun, might be relevant to hot-star X-ray production, continues to have adherents (Cassinelli & Olson 1979; Waldron 1984; Smith et al. 1993; Waldron & Cassinelli 2001; Smith et al. 2004). Indeed, models of surface magnetic field generation and dynamo mechanisms that do not involve envelope convection, and therefore might be applicable to massive stars, have recently been proposed (see e.g. Mullan & MacDonald 2005, and references therein). Speculation on the applicability of such models to massive stars, including specifically ζ Ori, has, in fact, been motivated by the claims of symmetric X-ray emission lines and anomalous X-ray line ratios in ζ Ori (Mullan & Waldron 2006). Finally, it has recently been suggested that a hybrid wind-magnetic shock-heating X-ray production mechanism is in operation on at least some hot stars (Babel & Montmerle 1997a,b; Gagné et al. 1997, 2005; ud-Doula & Owocki 2002; Schulz et al. 2003).

The launch of the *Chandra* and *XMM-Newton* telescopes in 1999, with their high-resolution grating spectrometers, vastly improved the quality of X-ray spectra available from OB stars. Although these missions provided a huge increase in the amount of information in the X-ray data, they have not led to a consensus in the community regarding the actual X-ray production mechanism in hot stars. This is partly because of the diverse behaviour seen in the dozen or so normal (not interacting binary) O stars thus far observed. And it is also partly due to the lack of connection between the diagnostics usually employed in the analysis of grating spectra of O stars and any quantitative physical model.

The high resolution of the new X-ray grating spectrometers provides a powerful diagnostic of plasma kinematics and location (via the effects of continuum absorption across a line), and thus potentially a discriminant among the various physical models, in the form of resolved emission-line profiles. Hot plasma embedded in a fast stellar wind produces Doppler-broadened emission lines, with the velocity and density structure dictating the detailed form of these profiles. Continuum absorption by the unshocked wind is stronger on the red sides of emission lines, as the redshifted photons originating in the far side of the wind traverse a larger column of material than those emitted from the front, blueshifted side. Overall, then, a wind-shock mechanism, in which the shock-heated plasma is embedded in a more or less spherically symmetric cold wind, should lead to broadened and asymmetric lines with a blueshifted centroid and a characteristic shape (MacFarlane et al. 1991; Ignace 2001; Owocki & Cohen 2001).

The diverse behaviour observed in the first hot stars observed with *Chandra* and *XMM-Newton* includes line profiles that are broad, shifted and skewed in the earliest O stars (Cassinelli et al. 2001; Kahn et al. 2001) but which are quite narrow in early B stars (Cohen et al. 2003; Mewe et al. 2003) and young O stars (Schulz et al. 2003; Gagné et al. 2005), with the X-ray emission lines of late-O supergiants, including ζ Ori, having a more intermediate morphology (Waldron & Cassinelli 2001; Miller et al. 2002).

The O4 star ζ Pup seems to be generally accepted as fitting the wind-shock paradigm, based on its line profiles. The broad, shifted and asymmetric profiles are qualitatively what is expected from a spherically symmetric wind source (Cassinelli et al. 2001). Quantitative analysis (Kramer, Cohen & Owocki 2003) shows that the hot

plasma is distributed throughout the wind above some minimum radius of emission that is approximately half a stellar radius above the photosphere; that it is distributed roughly as the density squared of the bulk wind; and that the kinematics of the hot plasma are consistent with the underlying beta-velocity law (Lamers & Cassinelli 1999) of the bulk wind. This same analysis does, however, show that there is significantly less continuum absorption than would be expected for a smooth, spherically symmetric wind having a mass-loss rate consistent with ultraviolet (UV) and $H\alpha$ observations and wind opacity consistent with models. This might be explained by a reduction in the mass-loss rate or by inhomogeneities in the wind ('clumping' or 'porosity'). To the extent that the wind-shock picture is applicable to ζ Pup, it has generally been supposed, however, that this very early-O star is the only hot star for which the standard wind-shock scenario can explain the *Chandra* observations.

The subject of this study, the late-O supergiant ζ Ori, meanwhile, has X-ray lines that are broad enough to be understood in the context of the wind-shock scenario (Waldron & Cassinelli 2001). It was originally reported, however, that there was no systematic trend in the Doppler shifts of the emission lines observed with *Chandra*, and additionally, that the forbidden-to-intercombination line ratio of Si XIII indicates a location so close to the photosphere that it could not be explained in the context of wind-shock models (Waldron & Cassinelli 2001). However, no quantitative assessment has yet been made of the line-profile shapes. In this paper, we quantitatively examine the shift and asymmetry in the X-ray emission lines on ζ Ori. We do this first by fitting Gaussians to the strong emission lines in the *Chandra* spectrum, and then by performing a non-parametric analysis of the line shift and asymmetry, and finally by applying the simple line-profile model that was successfully used to fit the X-ray emission lines in the *Chandra* spectrum of ζ Pup. We show that the X-ray emission lines in ζ Ori actually can be as well fit by standard wind-shock models as those in ζ Pup, with a similar finding of lower-than-expected wind absorption. We also discuss the results of our line-profile analysis of ζ Ori in light of a re-evaluation of the forbidden-to-intercombination line ratios that revises the earlier results to show no significant conflict with a wind-shock origin for the X-rays (Leutenegger et al. 2006).

In Section 2, we briefly describe the observational data and the properties of ζ Ori. In Section 3, we assess the blueshifts and skewness of the line profiles quantitatively but in a non-model-dependent way. In Section 4, we report on fits of an analytic, spherically symmetric wind emission and absorption-line profile model (Owocki & Cohen 2001) to nine lines in the *Chandra* spectrum of ζ Ori. In Section 5, we discuss the results of the model fitting and their interpretation, including how these results comport with other X-ray diagnostics, especially the helium-like forbidden-to-intercombination line flux ratios and UV absorption-line mass-loss diagnostics. Finally, we summarize our conclusions in Section 6.

2 THE CHANDRA DATA AND STELLAR PROPERTIES

The data analysed in this paper were obtained during the *Chandra* AO1 GO phase, using the ACIS-S/HETGS configuration, and made with nominal pointing at ζ Ori. The effective exposure time was 73.87 ks, with the data comprising two observation IDs 610 and 1524, taken on 2000 April 8 and 2000 April 9, respectively. In the combined data, 11 347 first-order Medium Energy Grating (MEG) counts were recorded. The dispersed spectrum is quite soft, as can be seen in Fig. 1, and there were significantly more counts in the MEG than in the High Energy Grating (HEG) spectrum, which had

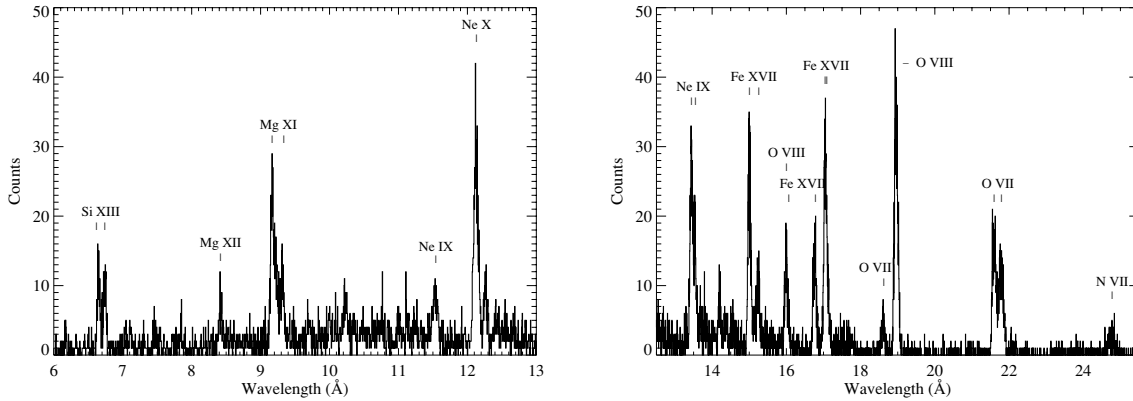


Figure 1. The MEG spectrum of ζ Ori, with negative and positive first orders from both observations (observation IDs 610 and 1524) co-added.

only 2508 total first-order counts. We therefore used only the MEG spectrum for the line-profile analysis in this paper. We performed the standard reduction and extraction of the dispersed spectra using the basic grating threads and CIAO v3.1 and CALDB v2.28. We checked the centroids of strong lines separately in the negative and positive first-order spectra and did not see any significant systematic shift in the wavelengths of the emission lines between the negative and positive sides. We wrote the count spectra (-1 and $+1$ orders) to ASCII files, and performed the analysis with custom-written codes in IDL and MATHEMATICA, except for the initial fitting of Gaussian line profiles, which we performed within XSPEC. We then repeated the fits of wind-profile models to individual lines using a custom-written model within XSPEC v11.3.1. For the XSPEC fitting, we used only observation ID 610 (exposure time of 59.63 ks), as including the second, much shorter, observation ID did not improve the statistics on the fits significantly. For all the model fitting reported on in this paper, we used the C statistic to assess the goodness of fit and parameter confidence limits, as the data in the line wings and nearby continuum have a small number of counts per bin (Cash 1979). We discuss the fitting procedure in detail in Section 4.

The late-O supergiant, ζ Ori (Alnitak, HD37742, the eastern most of the Orion belt stars), has a *Hipparcos* distance of 277^{+73}_{-49} pc (Perryman et al. 1997). It has a spectral classification of O9.7 and a luminosity class Ib (Maíz-Apellániz et al. 2004), and as such is significantly cooler than the O4 prototype ζ Pup, which shows X-ray emission-line profiles consistent with the wind-shock scenario. The wind mass-loss rate determinations for ζ Ori are roughly a factor of 2 lower than those for ζ Pup. Other important stellar and wind parameters taken from the literature are listed in Table 1. The overall X-ray properties of ζ Ori are quite typical of O stars ($kT_X < 1$ keV, $L_X/L_{\text{Bol}} \approx 10^{-7}$) (Cassinelli & Swank 1983; Berghoefler, Schmitt & Cassinelli 1996; Waldron & Cassinelli 2001).

3 PHENOMENOLOGICAL AND NON-PARAMETRIC ANALYSIS OF THE LINE PROFILES

The simplest method, and a common mode, of examining hot-star emission-line properties is the fitting of Gaussian line-profile models. These are convolved with the instrumental response function and multiplied by the instrument effective area and fit to individual lines allowing for an assessment of the centroid shifts, line widths and amplitudes. Indeed, this approach was taken in the paper that presented and first discussed the high-resolution *Chandra* spectra of ζ Ori (Waldron & Cassinelli 2001). Waldron & Cassinelli (2001) reported significant broadening (velocity dispersion of 900 ± 200 km s $^{-1}$), but also noted the generally symmetric appearance of the lines and reported a lack of any trend in line centroid shifts.

We recapitulate this approach here, but also quantitatively examine the quality of the Gaussian fits, including the distribution of the residuals. In Fig. 2, we look at two of the strongest unblended lines in the spectrum, O VIII Ly α at 18.969 Å and Fe XVII at 15.014 Å. In these fits, shown in the top panels of each column, the centroid of the Gaussian was first fixed at the laboratory rest wavelength (the oscillator-strength-weighted mean of the two components of the Ly α doublet in the case of the oxygen feature) and a power law was fit simultaneously to the weak continuum. These fits are formally bad when analysed using Monte Carlo simulations of the C statistic distribution—rejected at more than the 90 per cent level. There are clear indications of line-profile asymmetries in the residuals of the Gaussian fit, in the sense one would expect from a wind-shock model, with a blueshifted peak and steeper blue wings and shallower red wings.

We next fit a Gaussian model with the centroid allowed to be a free parameter. This model (shown in the middle panel of each column in Fig. 2) fits the line profile better, but there are clearly still

Table 1. Stellar properties of ζ Orionis from the literature.

Reference	M (M_{\odot})	R (R_{\odot})	M_v	$B - V$	\dot{M} ($10^{-6} M_{\odot} \text{ yr}^{-1}$)	v_{∞} (km s $^{-1}$)
Lamers & Leitherer (1993)	49	31	-7.0	—	2.51	2100
Prinja, Barlow & Howarth (1990)	—	—	—	—	—	1860
Blomme (1990)	37	—	-6.7	—	—	2400
Groenewegen, Lamers & Pauldrach (1989)	41	26	-6.6	—	—	2100
Voels et al. (1989)	34	24	—	-0.27	—	—
Wilson & Dopita (1985)	25	20	—	—	1.58	2190

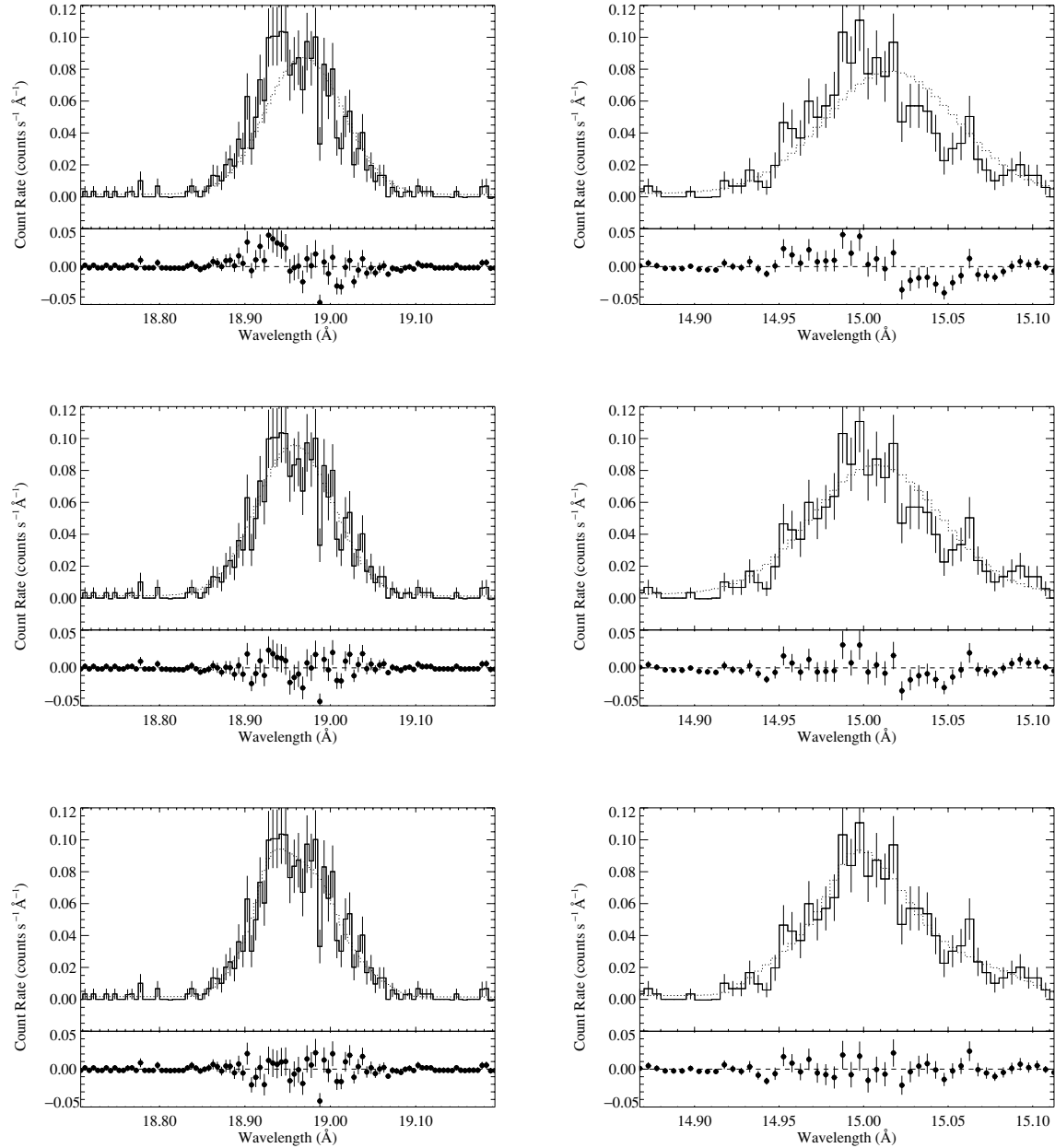


Figure 2. Best-fitting models superimposed on the observed O VIII Ly α line (left-hand column) and the Fe XVII 15.014 Å line (right-hand column). Error bars here and in other figures are calculated from the total source counts per bin, assuming Poisson errors. The fits shown in the top row are for a Gaussian model with the line centre fixed at the laboratory rest wavelength. These fits shown in the middle row are for the Gaussian model with the centroid treated as a free parameter. The Gaussian fits in the first two rows are discussed in Section 3. The fits shown in the lower panel are for the wind-profile model discussed in Section 4.

systematic trends in the distribution of fit residuals. Again, the actual line profiles have blue wings that are steeper than the Gaussians and red wings that are shallower. The Monte Carlo analysis of the C statistic distributions shows that these fits are better than those with the fixed Gaussian centroids, having rejection probabilities of only 68 and 73 per cent, for the O VIII and Fe XVII lines, respectively.

The widths and centroid shifts can be estimated from these Gaussian fits, even if the model is not ideal. For the oxygen Ly α line, we find a best-fitting Gaussian half width at half-maximum (HWHM) of 810 ± 30 km s $^{-1}$ and a centroid blueshift of -150 ± 30 km s $^{-1}$. Most other lines have even larger shifts, as can be seen in Table 2, in which we show the results of fits to seven emission lines in the

spectrum. These values seem plausible in the context of the windshock scenario, although one might ask what values of the peak blueshifts and HWHMs would be expected. The estimated terminal velocity of the wind is, after all, twice the value of the derived HWHMs. The answer will depend on the spatial distribution of the X-ray emitting plasma, the velocity distribution and the degree of attenuation (see fig. 2 in Owocki & Cohen 2001). We will show in the remainder of this section and the next one that there are quantitative indications of line asymmetries, even apart from the application of any specific wind model, and that an empirical wind model does in fact fit the line profiles better than the shifted Gaussian model (the wind-profile model is shown in the bottom two panels of Fig. 2,

Table 2. Gaussian line profile fits to the emission lines.

Ion	λ_o (Å)	Centroid (km s ⁻¹)	WHHM (km s ⁻¹)
N VII	24.781	-110 ± 140	1380 ⁺¹⁴⁰ ₋₁₃₀
O VIII	18.969	-150 ± 30	810 ± 30
O VII	18.627	-380 ⁺⁹⁰ ₋₈₀	500 ⁺¹²⁰ ₋₇₀
O VIII	16.006	-100 ⁺⁶⁰ ₋₈₀	880 ± 70
Fe XVII	15.014	-180 ⁺⁴⁰ ₋₅₀	830 ⁺⁵⁰ ₋₄₀
Ne X	12.134	-150 ± 50	980 ± 50
Ne IX	11.544	-390 ± 140	1360 ⁺¹⁶⁰ ₋₁₅₀

but not discussed until Section 4). Although we cannot reject the shifted Gaussian model with a high degree of certainty for any one emission line in the spectrum of ζ Ori, the Gaussian fitting suggests some degree of line-profile asymmetry and, more generally, that a more appropriate and physically meaningful model might improve the quality of the fits.

However, before fitting wind-profile models, let us first characterize the line-profile shapes using a model-independent, non-parametric analysis. We do this by computing the first three moments of the observed line profiles, describing, respectively, the centroid shift, width and asymmetry of the line profiles, as computed from

$$M_1 \equiv \frac{\sum_{i=1}^N x_i f(x_i)}{\sum_{i=1}^N f(x_i)},$$

$$M_2 \equiv \frac{\sum_{i=1}^N (x_i - M_1)^2 f(x_i)}{\sum_{i=1}^N f(x_i)},$$

$$M_3 \equiv \sum_{i=1}^N (x_i - M_1)^3 f(x_i).$$

Here, x is a dimensionless wavelength variable scaled to the terminal velocity of the wind, with the laboratory rest wavelength of each line set to $x = 0$, as $x \equiv (\frac{\lambda}{\lambda_o} - 1) \frac{c}{v_\infty}$, and $f(x_i)$ is the number of counts in the i th bin of N total bins at scaled wavelength x_i . Note that we have not normalized the third moment in our definition, in order to make the calculation of its formal uncertainty more straightforward. The standard definition of the skewness, s , is related to our definition of the third moment according to

$$s \equiv \frac{M_3}{M_2^3 \sum_{i=1}^N f(x_i)}.$$

We propagate the formal uncertainties for each calculated moment from the Poisson errors on the total number of counts in each (scaled) wavelength bin. We note that we have not corrected for the instrumental broadening, which is quite symmetric and not very large compared to the observed linewidths, and so will not affect the first and third moments significantly. We also have not corrected for the weak continuum present under each line or for the wavelength dependence of the detector-effective area. However, both of these factors are explored in quantitative detail in the next section, and are shown to be negligible. We list the values of the first and third moments for the stronger, unblended lines along with their formal uncertainties in Table 3. The second moments are not listed, although they are quite large, because we have already determined from the Gaussian fitting that the lines are broad and in the moment analysis we cannot separate out the effects of physical broadening from instrumental broadening. We use only the unblended lines in this analysis because the moment values have meaning only if they are calculated on a symmetric domain about $x = 0$. In all cases, we use the domain $[-1 : 1]$ and assume a value of $v_\infty = 1860$ km s⁻¹ for the wind terminal velocity. In Fig. 3, we show two emission lines, with the moment-analysis domains indicated, along with the laboratory rest wavelengths and the values of the first moments.

The numerical values of the first moments are straightforward to interpret. They represent the position of each line centroid in units of x . The values of the third moments, however, are difficult to interpret by themselves. However, their significance level in terms of formal uncertainties (i.e. their ‘sigma’ levels, listed in the final column of Table 3) is the relevant quantity for assessing whether each line has a non-zero skewness (asymmetry) that is statistically significant. Unshifted and symmetric lines should have first and third moments that are consistent with zero. The emission lines analysed for ζ Ori are significantly blueshifted (negative first moments), which is consistent with the results of the Gaussian fitting, but which contradicts the assertion of Waldron & Cassinelli (2001) that there are no systematic redshifts or blueshifts in the emission lines. It is also clear from the moment analysis that the lines are significantly redward skewed (positive third moments), generally between the 1 and 2 σ levels for each line. This asymmetry was not noted in the earlier analysis, which relied on ‘eyeballing’ the Gaussian fits (Waldron & Cassinelli 2001). A redward skewness (along with the blueshifted centroids) is exactly what is expected from continuum absorption in the context of a fast, spherically symmetric stellar wind (Owocki & Cohen 2001). The redward skewness comes about from the steep blue wing and the more extended, shallower red wing.

Table 3. First and third moments of the emission-line profiles.

Ion	λ_o (Å)	M1	M1/uncert.	M3	M3/uncert.
O VIII	18.969	-0.0818 ± 0.0135	-6.08	7.9914 ± 4.8511	1.65
O VII	18.627	-0.1138 ± 0.0416	-2.74	4.5943 ± 2.9983	1.53
Fe XVII	16.780	-0.1652 ± 0.0229	-7.32	7.5967 ± 3.9259	1.94
O VIII	16.006	-0.0464 ± 0.0247	-1.88	3.9309 ± 3.8114	1.03
Fe XVII	15.014	-0.0792 ± 0.0173	-4.58	12.5198 ± 5.5363	2.26
Ne X	12.134	-0.0801 ± .0194	-4.13	10.1529 ± 5.4936	1.85
Ne IX	11.544	-0.1108 ± 0.0368	-3.01	2.8778 ± 4.0377	0.71

Note: M1 and M3 are the first and third moments of the line profiles, respectively. The following columns show the ratio of the values of these moments, for the indicated unblended lines, to their formal uncertainties. We interpret the values in these columns as significance indicators of the first and third moments’ deviation from zero, as described in Section 3.

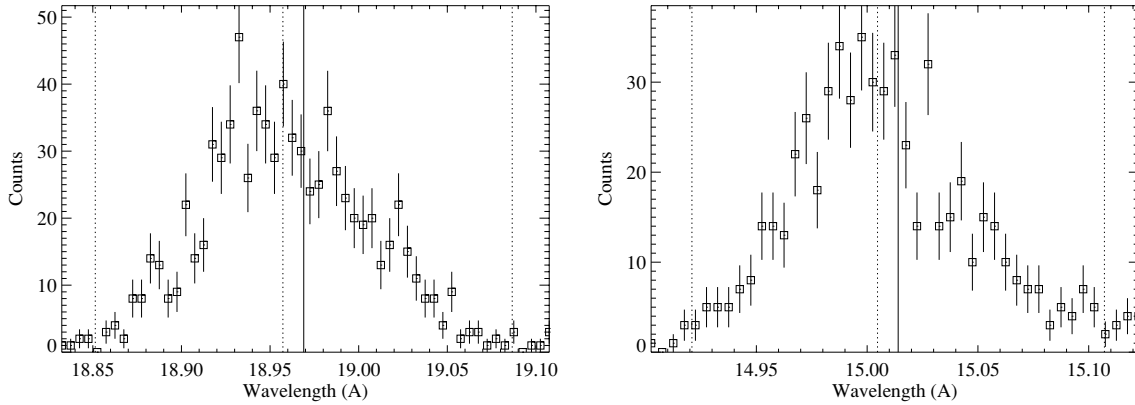


Figure 3. The same two representative emission lines shown in Fig. 2, with their centroids as determined from the moment analysis. O VIII Ly α at 18.969 Å (left-hand panel) has a centroid (first moment) 6σ from the laboratory rest wavelength, and a positive third moment (red skewed) that is significant at the 1.7σ level. The Fe XVII line at 15.014 Å (right-hand panel) has a significantly negative first moment (5σ) and a third moment that is positive at the 2.3σ level (see Table 3). In both panels, the solid vertical line is the laboratory rest wavelength, while the dashed line to its immediate left represents the first moment. The other two dashed lines represent the blue and red limits over which the moment analysis was performed ($x = -1, 1$).

4 WIND PROFILE MODEL FITS TO THE EMISSION LINES

In the previous section, we showed that there is evidence for blueshifting, redward skewness and broadening in the X-ray emission lines of the O supergiant ζ Ori. These results are consistent with the expectations of a generic wind-shock picture. To augment this model-independent characterization of the net profile shift and skewness, and to derive physical information about the applicability of a wind-shock model, let us next fit a simple, empirical wind-shock line-profile model to the relatively strong lines in the MEG spectrum of ζ Ori. We use the empirical wind-profile model of Owocki & Cohen (2001), which is physical, in the sense that it accounts for the Doppler-shifted emission and radiation transport, including continuum attenuation, through a three-dimensional, spherically symmetric expanding wind. The parameters of the model have specific, physical meanings related to the spatial distribution of the hot plasma and the amount of absorption by the bulk, unshocked wind. The model is empirical, in that it does not posit any specific heating mechanism, and thus is applicable to a wide range of possible wind-shock (and even coronal) scenarios for X-ray emission.

The goal of fitting the wind-profile model is thus to constrain the physical parameters of the wind emission and absorption for each strong emission line in the *Chandra* spectrum of ζ Ori. Theorists may then compare the predictions of any number of specific models or numerical simulations to the physical parameter values we derive. Furthermore, our fitting of wind-profile models allows us to quantify the amount of asymmetry in the line profiles and relate the asymmetry, quantitatively, to the amount of wind absorption, through the optical depth parameter of the wind-profile model

$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi v_\infty R_*},$$

where κ is the absorption opacity and \dot{M} is the mass-loss rate. Note that bound-free continuum absorption is the dominant opacity source. Physically, τ_* represents the optical depth along a central ray from infinity to the stellar surface radius R_* , in the simplified case that the wind velocity is constant at the terminal value, v_∞ . In this simplified, constant-velocity case, a value of $\tau_* > 1$ also represents the radius of unit optical depth, R_1 , expressed in units of R_* . The wind-profile model assumes that the hot plasma is dis-

tributed throughout the wind, above some minimum radius, R_{\min} , and that its filling factor is proportional to the ambient wind density multiplied by an additional power-law factor, $f \propto r^{-q}$ (thus falling off as $1/vr^{(2+q)}$). The other two interesting parameters of the model are thus R_{\min}/R_* (sometimes expressed as $u_{\max} \equiv R_*/R_{\min}$) and q . The normalization of the profile is the fourth, and final, parameter. There is an implicit assumption that there are enough different regions of hot plasma that the wind can be treated as a two-component fluid, comprising a bulk, cool ($T \approx T_{\text{eff}}$), X-ray absorbing component, with a hot, X-ray emitting component smoothly mixed in. The minimum radius of the hot plasma distribution is motivated by numerical simulations that show that large shocks tend not to form until the wind flow has reached at least several tenths of a stellar radius (Cohen et al. 1996; Cooper 1996; Feldmeier et al. 1997b).

As discussed in further detail in Owocki & Cohen (2001), the line profile is computed from the integral

$$L_x \propto \int_{r=r_x}^{\infty} \frac{r^{-(q+2)}}{(1 - R_*/r)^{3\beta}} \exp[-\tau(\mu_x, r)] dr,$$

where $r_x \equiv \max[R_{\min}, R_*/(1 - |x|^{1/\beta})]$, $\mu_x \equiv x/(1 - R_*/r)^\beta$ and $\tau(\mu, r)$ (which is proportional to τ_*) is the optical depth along the observer's line of sight at direction cosine μ and radial coordinate r . Here, the scaled wavelength, $x \equiv (\lambda/\lambda_o - 1)(c/v_\infty)$, is the same quantity we used in the moment analysis. The parameter β is the usual wind acceleration parameter, from $v = v_\infty(1 - R_*/r)^\beta$. The governing equation for L_x must be solved numerically for all $\beta \neq 0$. We set $\beta = 1$ in all of our fits.¹ We include a power-law continuum model in all the fits we performed in XSPEC. Finally, we note that this

¹ The exact value of β is not known for any given star, but its canonical value is $\beta = 0.8$. Numerical simulations indicate that the X-ray emitting plasma follows a velocity law not too different from the bulk wind (Feldmeier et al. 1997b; Runacres & Owocki 2002). And recent work that takes wind clumping into account finds values of β that are generally even closer to unity than 0.8 (Puls et al. 2006). Furthermore, the difference between $\beta = 0.8$ and $\beta = 1$ is quite small, in terms of the actual wind velocity (Lamers & Cassinelli 1999). Given the lack of certainty about the exact value that should be used, and the lack of sensitivity to the specific value – within reason – we choose to use $\beta = 1$ because non-integer values of β require a numerical solution of the optical depth integral in the line-profile model.

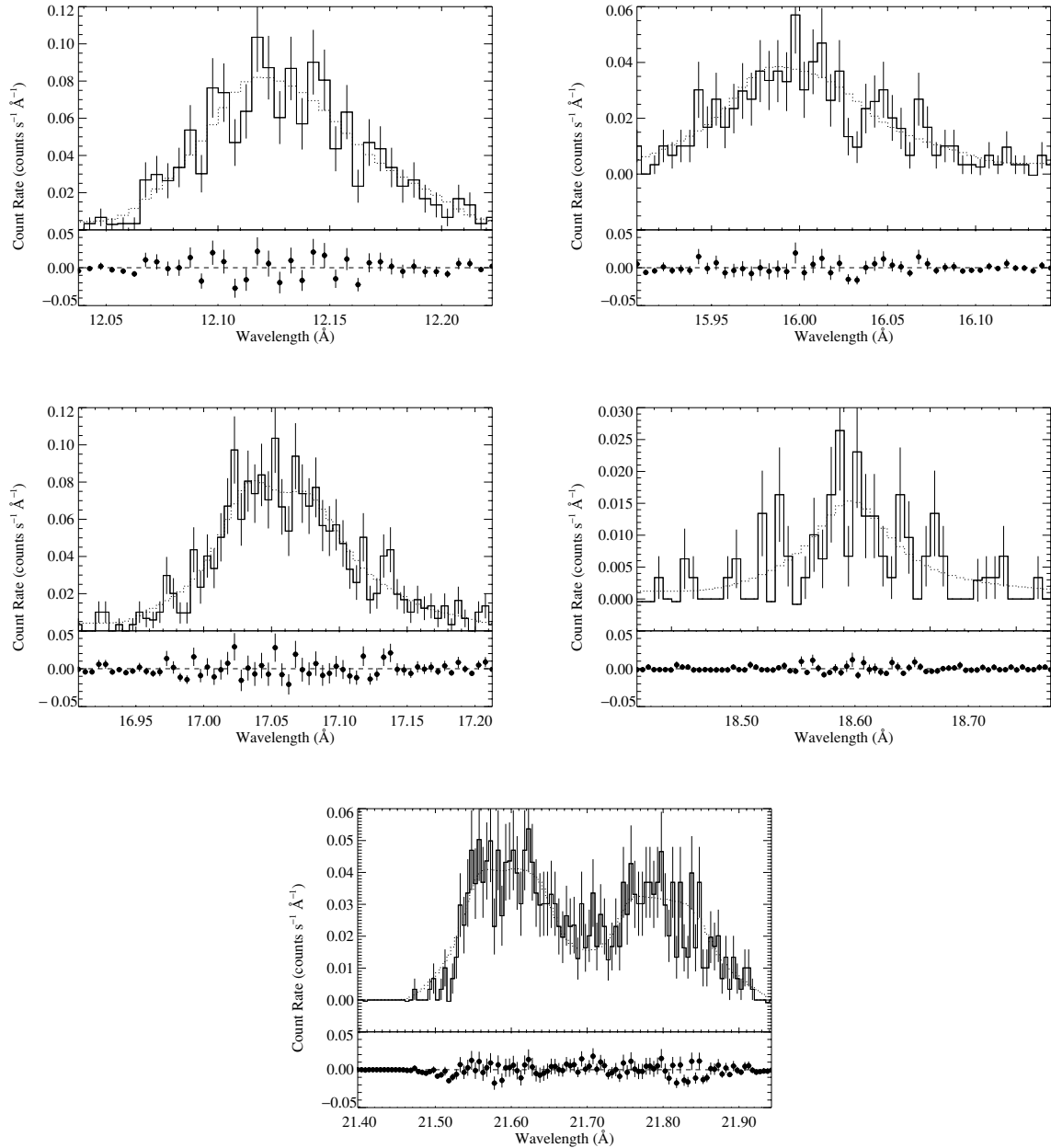


Figure 4. Best-fitting wind-profile models for five lines (or line complexes): Ne x 12.134 Å, O VIII 16.006 Å, Fe XVII 17.051 Å and 17.096 Å, O VII 18.627 Å and O VII 21.602 Å and 21.804 Å.

profile model implicitly assumes spherical symmetry and a smooth wind flow.

Again, this wind-profile model is both physically meaningful and widely applicable to a range of different physical models of X-ray production, including coronal models (see fig. 2 in Owocki & Cohen 2001, for a graphical exploration of the effects of choosing different model parameter values on the line-profile shapes, and fig. 4 in the same paper for a comparison of wind-shock and coronal model parameters). The larger R_{\min} is and the smaller q is, the broader the line profiles tend to be. We note that for a wide range of realistic choices of these parameters, the characteristic width of the resulting profiles is equivalent to roughly half the terminal velocity, consistent with the half-widths we derived from the Gaussian fits in the previous section. Increasing the wind optical depth parameter, τ_* , tends to make the profiles more narrow, more blueshifted and more asym-

metric. A model with a relatively small R_{\min} value and a negligible τ_* produces a profile that is similar in shape to a Gaussian.

We fit this wind-profile model to each strong line in the ζ Ori MEG spectrum, allowing all four adjustable parameters (τ_* , R_{\min} , q and the normalization) to be free, in conjunction with a power-law component to model the weak continuum emission. For several line complexes, we fit multiple profiles simultaneously to account for blending. This included the helium-like resonance and intercombination lines of oxygen. We do not give fits to the other helium-like complexes in the ζ Ori *Chandra* spectrum, as fits to these complexes are reported elsewhere (Leutenegger et al. 2006). For the Fe XVII lines at 17.051 Å and 17.096 Å (3G and M2, respectively), which we fit simultaneously, because they are quite blended, we fixed the relative normalizations to $I(M2)/I(3G) = 0.8$, consistent with HULLAC calculations (Mauche, Liedahl & Fournier 2001) and

Table 4. Wind profile model parameters fit to the data.

Ion	λ_o (Å)	q	R_{\min}/R_*	τ_*	Goodness of fit ^a
O VII	21.804, 21.602	$-0.30^{+0.27}_{-0.19}$	$1.66^{+0.15}_{-0.13}$	$0.06^{+0.14}_{-0.06}$	0.33
O VIII	18.969	$-0.12^{+0.29}_{-0.22}$	$1.61^{+0.14}_{-0.12}$	$0.26^{+0.20}_{-0.13}$	0.67
O VII	18.627	$0.39^{+1.38}_{-0.71}$	$1.29^{+0.29}_{-0.18}$	$1.34^{+1.86}_{-0.74}$	0.49
Fe XVII	17.051, 17.096	$-0.41^{+0.29}_{-0.19}$	$1.28^{+0.21}_{-0.13}$	$0.76^{+0.52}_{-0.33}$	0.40
O VIII	16.006	$-0.41^{+0.41}_{-0.31}$	$1.51^{+0.98}_{-0.25}$	$0.27^{+0.48}_{-0.19}$	0.53
Fe XVII	15.014	$-0.47^{+0.22}_{-0.16}$	$1.37^{+0.15}_{-0.14}$	$0.58^{+0.41}_{-0.25}$	0.29
Ne X	12.134	$-0.50^{+0.35}_{-0.21}$	$1.55^{+0.32}_{-0.21}$	$0.45^{+0.46}_{-0.29}$	0.14

^aFraction of Monte Carlo simulated data sets that gave a C statistic as good or better than that given by the best-fitting model and the data. This can be interpreted as a rejection probability. Lower values indicate better fits.

with the values generally observed in stars. When fitting these lines, and also other line blends, we tied the three primary parameters of the line-profile model – τ_* , R_{\min} , q – together. Ultimately, we report here on the fits to the nine lines in the spectrum that provide meaningful constraints to the model parameters. Note that these are not the same set of lines to which we fit Gaussian models, as it was easier to get meaningful Gaussian fits to several weaker lines and it was harder to get meaningful Gaussian fits to the blended lines.

As mentioned previously, we first carried out this modelling using the same procedure, implemented in MATHEMATICA, that we employed in our earlier analysis of ζ Pup (Kramer et al. 2003). We then repeated the modelling using a custom-written module in XSPEC, which allowed us to include a continuum emission component in the modelling and use the exact instrumental responses. This also enabled us to simultaneously fit multiple models to line blends. The two methods gave very similar results, and the XSPEC fits were insensitive to both the choice of continuum model and the wavelength range included in the fit. The results of the XSPEC model fitting are summarized in Table 4, and the best-fitting models, superimposed on the data, are shown in Fig. 4 and the bottom row of Fig. 2 for the nine lines, in seven complexes, for which we could obtain meaningful fits. The wind-profile model does indeed provide better fits to the stronger, unblended lines than does the Gaussian model, according to the Monte Carlo simulations of the distribution of C statistic values. The goodness of fit values (expressed as a percentage of the Monte Carlo simulations that gave a C statistic as good as or better than that derived from the fit to the actual data; lower percentages are better) is listed in Table 4. All the wind-profile fits are formally good.

We calculated errors on the derived model parameters by using a three-dimensional grid of models in the parameter space of interest ($\tau_*-R_{\min}-q$) and applying a ΔC criterion appropriate for jointly distributed uncertainties for three parameters, and report the maximum extent of this confidence region in each of the three parameters as the formal uncertainties on the derived parameters. These are the values listed in Table 4 (90 per cent confidence limits for one parameter of interest – $\Delta C = 2.71$), and shown, for two particular fits, in Fig. 5.

5 DISCUSSION

We summarize the derived model parameters and their uncertainties for each line in Fig. 6. This figure shows that there are no strong trends in any of the wind-profile model parameters with wavelength (or any other characteristic) of the emission lines. Fitting a function

linear in wavelength to the uncertainty-weighted model parameters shows consistency with a constant function (at the 95 per cent confidence level) for each of the three parameters. Note that the τ_* point for the O VII complex near 22 Å must be excluded for this statement to be true. We discuss this outlier in terms of the wavelength dependence of the wind opacity near the end of this section.

The fitting results shown in Fig. 6 present a consistent picture of a line-profile model with $\tau_* \approx 0.25-0.5$, an onset radius $R_{\min} \approx 1.5 R_*$ and a constant filling factor ($q \approx 0$). These are all reasonable parameters in the context of the general instability-driven wind-shock model, though the τ_* values are small compared to the expectations of wind theory, which we elaborate on below. Finally, we note that most of the lines cannot be well fit by models with no wind absorption ($\tau_* = 0$ is ruled out), which is consistent with the inability of Gaussian models to provide good fits and also with the non-zero third moments of the line profiles, as discussed earlier. Looking at the situation from a different point of view, upper limits on the wind absorption are above $\tau_* \approx 0.5$ for all but one line complex in the spectrum. The unmistakable conclusion is that the *Chandra* spectrum of ζ Ori is consistent with a moderate amount of wind absorption (as well as the expected degree of broadening from an embedded wind source), and that at least some wind attenuation is demanded by the data.

The derived R_{\min} and q values are consistent with the numerical simulations of the line-force instability wind shocks, inferred from simulation output shown in various figures in Cooper (1996), Cohen et al. (1996), Feldmeier et al. (1997b) and Owocki & Runacres (2002). These trends are also qualitatively understood from a theoretical point of view. The strong, relatively symmetric diffuse (scattered) radiation field near the photosphere inhibits the line-force instability and thus the formation of strong shocks near the photosphere, and the filling factor is not strongly dependent on radius because although the propensity of shocks to form eventually falls off with distance from the photosphere, the cooling time-scale for shock-heated plasma increases with distance.

Given the spatial distribution of hot plasma derived from the line-profile fits, the continuum attenuation by the overlying cool wind is governed by the mass-loss rate and wind opacity. In the model we have employed, the overall wind attenuation is characterized by the optical depth parameter

$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi v_\infty R_*}.$$

Using mean values from Table 1 and a wind opacity value of $\kappa \approx 125 \text{ cm}^2 \text{ g}^{-1}$, we expect $\tau_* \approx 3$. The value for the wind opacity is taken from fig. 4 in Cohen et al. (1996) and is consistent with

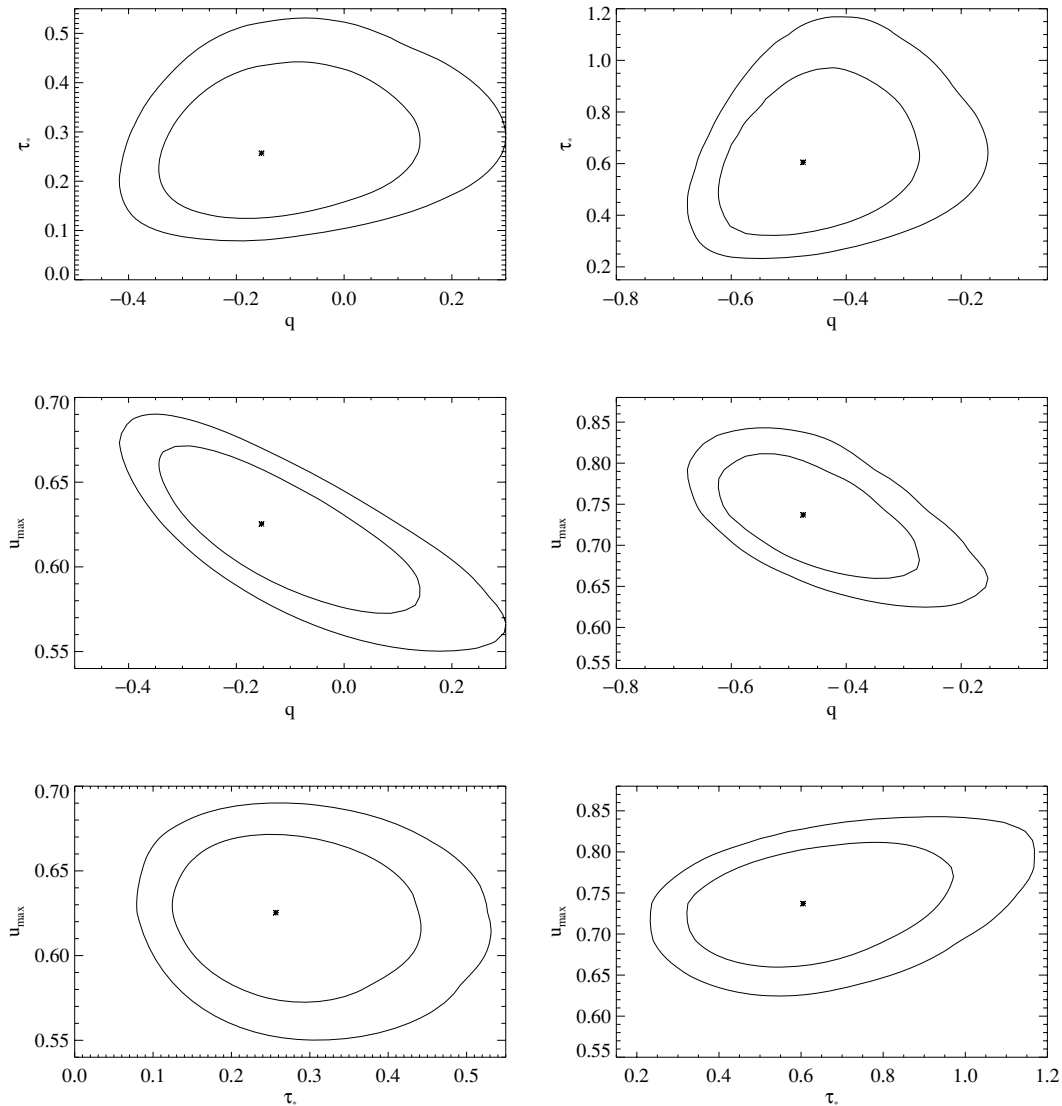


Figure 5. The 68 and 90 per cent confidence regions in the parameter space of the wind-profile model, for the two lines shown in Fig. 2, the O VIII Ly α line (left-hand column) and the Fe XVII 15.014 Å line (right-hand column). The best-fitting model parameters are indicated by the asterisks. Note the correlation between q and $R_{\min}/R_*(u_{\max}^{-1})$. For each 2D slice of parameter space shown here, the other model parameters are optimized (i.e. free), while models are fit for a grid of the two displayed parameter values. The contour levels thus correspond to ΔC values appropriate for two parameters of interest, 2.30 and 4.61.

fig. 4 in Oskinova, Feldmeier & Hamann (2006). Of all the values that go into this calculation, the mass-loss rate is probably the most uncertain, followed by the wind opacity and the star's radius. The terminal velocity is probably known to within 10 or 20 per cent (which is the range of values found in the literature).

Thus, the value of the wind optical depth parametrized by τ_* , as derived from the observed X-ray line profiles, is about an order of magnitude lower than the expected value. This is similar to what is seen in ζ Pup (Kramer et al. 2003), where the observed value of τ_* is almost an order of magnitude lower than expected (there is also a fair amount of uncertainty in the relevant properties of ζ Pup). The expected τ_* value for ζ Pup is about a factor of 2 larger than that for ζ Ori, primarily because of the earlier type star's larger mass-loss rate.

The fact that the X-ray line profiles of ζ Pup, and now ζ Ori, indicate lower than expected wind optical depths is consistent with recent work that suggests that O star mass-loss rates may have been overestimated by a factor of 3 or more, and perhaps up to an

order of magnitude (Bouret, Lanz & Hillier 2005) due to clumping (which affects density-squared mass-loss diagnostics, such as radio free-free and H α emission). This result is not inconsistent with the traditional UV absorption line-based mass-loss rate estimates of hot-star winds, which have always been subject to uncertainty due to the difficulty of reliably accounting for ionization distribution effects. In fact, other recent work, focusing on far-UV absorption-line studies as diagnostics of mass loss and wind ionization in many O and B supergiants, indicates that mass-loss rates based on UV absorption-line analysis may be overestimated by as much as an order of magnitude (Fullerton, Massa & Prinja 2006).

Recent detailed multiwavelength modelling of a large sample of O giants and supergiants (but not including ζ Ori) indicates mass-loss rate overestimates of at least a factor of 2, assuming that the far wind, where the radio free-free emission arises, is unclumped, and more than a factor of 2 if the far wind is significantly clumped (Puls et al. 2006). This work also shows that there are star-to-star variations in

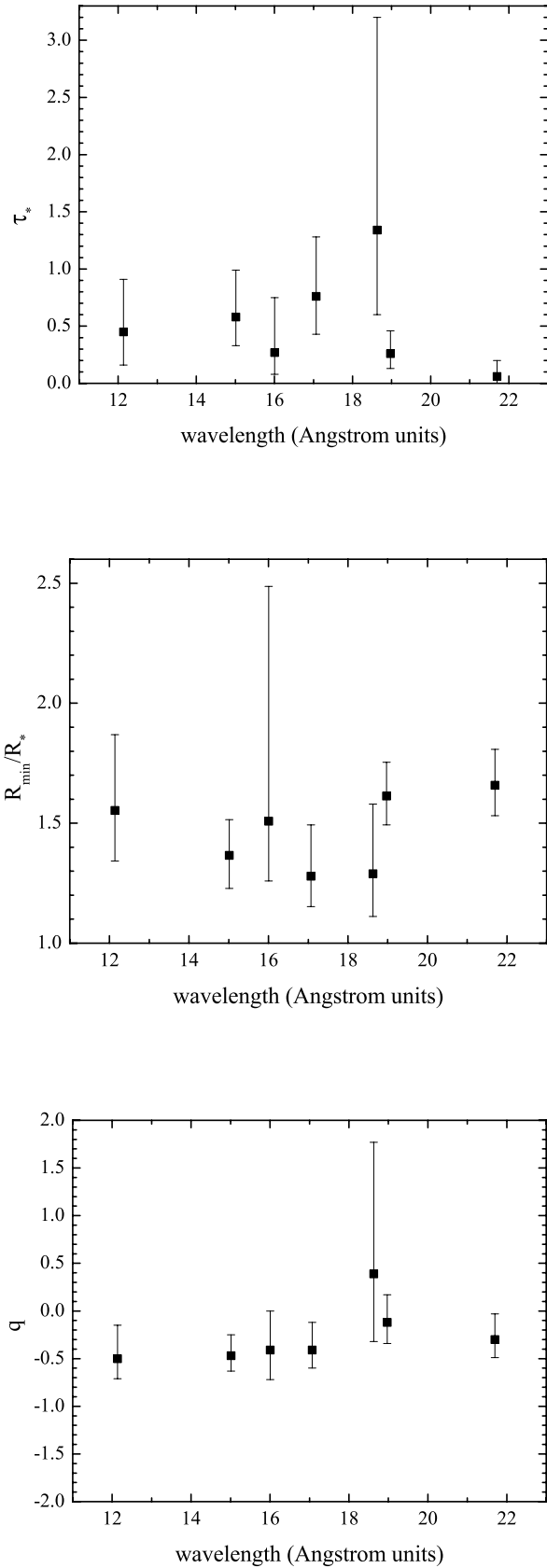


Figure 6. The best-fitting model parameters – τ_* , R_{\min} and q – for each line complex we fit with a wind-profile model. The error bars represent the 90 per cent confidence limits on the one parameter of interest in each panel ($\Delta C = 2.71$).

clumping factors and a somewhat strong radial dependence – at least for some stars – to the clumping factor. We note in this context that the X-ray profiles will in general be most sensitive to clumping in the region near and just above R_{\min} (so, $R \approx 2 R_*$, which is ‘region 2’ in the analysis of Puls et al. 2006). These various threads of evidence for lower mass-loss rates are also consistent with the energy budget analysis of wind-blown bubbles and superbubbles (see e.g. Nazé et al. 2002, Cooper et al. 2004 and references therein; but see also Freyer, Hensler & Yorke 2006 for the role played by the swept-up wind from earlier evolutionary stages in Wolf–Rayet bubbles).

Even apart from its effect on mass-loss rate estimates, clumping itself has the potential to reduce the effective opacity of a stellar wind (Feldmeier, Oskinova & Hamann 2003; Oskinova, Feldmeier & Hamann 2004). This effect might more accurately be termed ‘porosity’, as it presumes the existence of a low-density interclump channels that can potentially allow photons to escape the wind more easily (Owocki, Gayley & Shaviv 2004). Oskinova, Feldmeier & Hamann (2005, 2006) have recently computed X-ray line profiles for specific models incorporating geometrically thin, radially compressed shells, comparing their results with observed profiles for several hot stars (including ζ Ori). Within the assumptions in their model, these authors show that a very optically thick emission line, with a significant skewness in a smooth wind, can be made moderately more symmetric with an interclump spacing of $0.2 R_*$, and can be made nearly symmetric with an interclump spacing of $2 R_*$ (see fig. 1 in Oskinova et al. 2005). Similarly, using a parametrized model of isotropic clumping, based generally on the porosity formalism introduced by Owocki et al. (2004) and Owocki & Cohen (2006), find that obtaining symmetric X-ray emission profiles from an otherwise optically thick wind requires a quite large ‘porosity length’ $h \equiv \ell/f$, where ℓ represents the characteristic clump scale and f is the clump volume filling factor. Specifically, it requires h of the order of the local radius r .

In this context, it is thus important to stress that while the mass-loss overestimates due to clumping depend only on the density contrast between the clumps and the interclump medium (and thus the volume filling factor), for porosity to affect the line profiles directly, the density contrast must be accompanied by a large clump scale, or interclump spacing. The most sophisticated numerical treatment of the line-force instability shows structure on small ($\ell \ll R_*$) spatial scales, with only moderately compressed volume filling factors ($f \approx 0.1$; Dessart & Owocki 2003).

These results make it difficult to see how the wind inhomogeneities produced by the instability and which, presumably, are directly related to the shock-heating responsible for the X-ray emission itself, could lead to a significant porosity effect on the X-ray line profiles. In light of the several independent lines of evidence for lower O star wind mass-loss rates, we suspect that lower wind column densities are the cause of the order of magnitude discrepancy between the τ_* values we derive in this paper from fits to the emission lines in the *Chandra* spectrum of ζ Ori and the similar results derived by Kramer et al. (2003) for ζ Pup. Clumping and the associated porosity may play some role, but for that role to be significant, the porosity length in O star winds must be large – of the order of the local radius – and the combination of these two effects must reduce the effective wind optical depth by an order of magnitude.

The results from our X-ray emission-line profile analysis should be consistent with other aspects of the *Chandra* observations. The emission measure and temperature information derived from the observations (Cassinelli & Swank 1983; Berghoefter et al. 1996; Waldron & Cassinelli 2001) are typical for O supergiants and do

not provide any significant constraints on the interpretation of the line profiles, aside from simply being broadly consistent with the expectations of the standard wind-shock scenario. The most constraining specific X-ray diagnostic in conjunction with the emission-line profiles is the forbidden-to-intercombination emission-line ratio in the helium-like isoelectronic sequence (Gabriel & Jordan 1969; Blumenthal, Drake & Tucker 1972). In the presence of a strong UV field which can drive photoexcitation of electrons from the upper level of the forbidden line to the upper level of the intercombination line ($2s^3S_1-2p^3P_{1,2}$) and thus reduce the f/i line ratio, it can be used as a diagnostic of the UV mean intensity and thus of the distance of the X-ray emitting plasma from the photosphere.

The initial work on the several helium-like f/i ratios seen in the *Chandra* spectra from ζ Ori showed that most of the helium-like ions were far from the photosphere, consistent with those ions being embedded in the stellar wind, but that the Si XIII f/i ratio implied a location only slightly above the photosphere, which would generally be considered too close to the star to be consistent with any wind-shock scenario (Waldron & Cassinelli 2001). However, a recent reanalysis of these same data showed that all the helium-like ions, including Si XIII, are consistent with an onset radius (R_{\min}) of about $1.5 R_*$ (Leutenegger et al. 2006). This result is, of course, completely consistent with those we report here for the emission-line profiles of nine other lines in the *Chandra* data.

We can also consider trends in the derived wind profile parameters within our data set. One might expect different lines to have different morphologies and thus different model parameters either because different ions form at different temperatures and thus sample different shocked regions or because lines at different wavelengths have differing amounts of wind attenuation due to the wavelength dependence of the opacity of the bulk, cold wind. Regarding the first possible effect, we note that numerical simulations show a relatively constant rms velocity dispersion with radius, once shocks begin to form (Runacres & Owocki 2002). Fig. 5 in Runacres & Owocki (2002) shows, in detail, a very rapid rise in the velocity dispersion, followed by a very shallow fall-off with radius.

Regarding the second effect, that of wavelength-dependent attenuation, photoionization cross-sections of cosmically abundant plasma do have a strong wavelength dependence over a large range of wavelengths. However, this effect is more complex when the plasma is ionized, as it is even in the ‘cold’ component of a hot-star wind. Furthermore, the lines we analyse in this paper span only a factor of 2 in wavelength. Looking at the wind opacity in fig. 4 of Cohen et al. (1996), we can see that the values of the wind opacity range only over about a factor of 2 from 600 (roughly the photon energy of the O VII lines near 22 Å which are the longest wavelength lines to which we fit the wind profile model) to 1000 eV (roughly the photon energy of the Ne X Ly α line, which, at $\lambda = 12.134$ Å, is the shortest wavelength line we discuss here). The variations in the wind opacity on this relatively small wavelength range are complex and not monotonic because of the dominance of photoionization edges of oxygen (O⁺³ through O⁺⁵). The appearance of these edges breaks up the usual E^{-3} fall off in opacity, and over this relatively small wavelength range, makes the opacity roughly constant. If anything, the longest wavelength lines in our data (the O VII lines near 22 Å) are subject to less attenuation than the shorter wavelength lines, by virtue of their being longward of the oxygen K -shell edges (and, in fact, this emission feature has the lowest upper limit to the τ_* parameter of any of the lines we fit). In any case, there are no significant systematic trends in any of the three wind-profile model parameters. As we discussed above, a single value of each parameter is consistent with all the data. Therefore, although higher signal-to-

noise ratio data in the future may reveal a significant trend, none is seen in these data. We should point out, though, that Oskinova et al. (2006) noted that radiation transport through a medium with completely optically thick clumps will not only reduce the effective wind opacity, but will make the opacity effectively grey. Interpreting the wavelength dependence of line-profile morphologies—or lack thereof—however, requires both a detailed evaluation of the wavelength-dependent atomic opacity and its uncertainty, and also statistical fitting of whatever line-profile model may be appropriate along with formal constraints on confidence limits of the parameters of that model.

Finally, we note that each line or line complex is well fit, in a statistical sense, by the relatively simple, spherically symmetric wind-profile model we employ here. Future higher resolution and/or higher signal-to-noise ratio spectra could show evidence for signatures of wind asymmetry or of time variability in the line profiles (perhaps much like discrete absorption components seen in UV absorption lines from the winds of hot stars or like moving emission bumps seen in Wolf–Rayet spectra). There is, however, no need at this point to invoke either of these effects or of any others that go beyond the basic model we have used here.

6 CONCLUSIONS

The fundamental observational conclusions of this work are that the X-ray emission lines of the late-O supergiant ζ Ori are broad, blueshifted and modestly asymmetric, which is qualitatively consistent with the general picture of hot, X-ray emitting plasma embedded in an expanding, spherically symmetric stellar wind. These results come both from fitting a physics-based empirical wind-profile model to nine emission lines in the *Chandra* MEG spectrum, and also from attempts to fit Gaussian line-profile models and a non-parametric analysis of the line shapes via the calculation of the first three moments of seven unblended lines.

There is no need, based on the observed line profiles, to invoke ad hoc coronal emission or other non-standard X-ray production mechanisms. However, the amount of attenuation by the bulk, cold stellar wind is significantly less than would be expected by a simple application of the assumed mass-loss rate, standard warm plasma opacities and the assumption of a spherically symmetric, smooth stellar wind. Qualitatively, this result is consistent with the results of a similar analysis of the *Chandra* spectrum of the early-O star, ζ Pup (Kramer et al. 2003). And the smaller-than-expected wind attenuation leaves an observational signature that explains why previous studies, in which Gaussian profiles were fit and then analysed ‘by eye’, did not identify the signature of wind attenuation. The emission lines, though significantly blueshifted, are only modestly asymmetric, and in fact, any individual line can be at least marginally fit by a blueshifted Gaussian. For the strongest lines, however, there is a significant improvement in the fits based on the wind-profile models as compared to those based on Gaussians.

These results, taken together with the earlier ones on the X-ray line profiles of ζ Pup, indicate then that the standard wind-shock scenario is adequate for explaining the high-resolution X-ray spectra for normal O supergiants. Unusual hot stars, such as θ^1 Ori C and τ Sco, do not fit into this paradigm, perhaps because of their extreme youth, but there is no reason, especially now that the helium-like f/i line ratios have also been reanalysed (Leutenegger et al. 2006), to suppose that all hot stars, with the sole exception of ζ Pup, pose an insurmountable challenge to the wind-shock model of X-ray production. That being said, the wind-shock model still has various difficulties in accounting in detail for the observed trends in X-ray

properties among OB stars, and there are many open questions about the specific ingredients of a correct wind-shock model. However, the nature of X-ray emission-line profiles in O supergiants, while providing some interesting constraints and presenting a puzzle about wind optical depths, does not require us to completely discard the wind-shock paradigm or lead us to invoke coronal models for explaining hot-star X-ray emission. The lower than expected wind optical depths derived from the X-ray line profiles do, however, add to the debate about O star mass-loss rates and the role of wind clumping.

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