Spectral Modeling of X-rays from Hot Star Winds

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We attempt to determine the mass-loss rates of several O stars using x-ray spectra from *Chandra's* archive. Models of x-ray production in hot star winds predict broad, asymmetric emission lines, but observed lines tend to be much more symmetric. Such symmetry can be explained by either lowering the values of the mass-loss rate for these winds, or by reassessing the commonly accepted models of x-ray production. Previous explorations of the trade-offs of these two options have been largely qualitative in nature. In our research, we thus seek to quantify the amount of asymmetry present in the data and to find the reductions in mass-loss rate values needed to explain the data.

Introduction

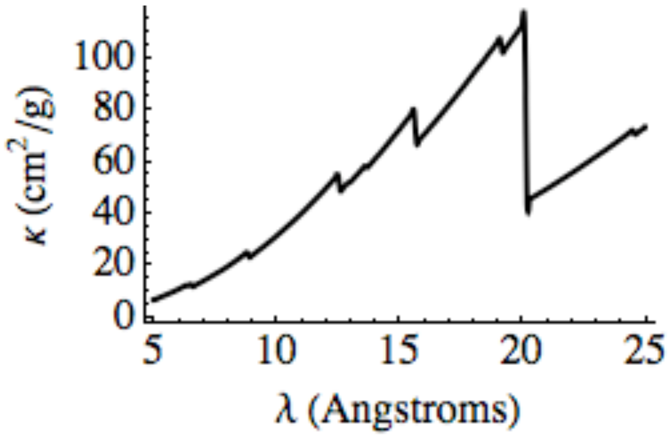
O stars have continually captured the interest of astronomers, and it is not difficult to understand why. These stars, with masses up to a hundred times that of the sun, luminosities up to a million times that of the sun, and lifetimes of only one to ten million years, represent a stellar extreme. Moreover, they are responsible both for the production of the heavy elements that are so familiar (and fundamental) to us on Earth, and for the production of some of the most exotic objects in our galaxy – black holes and neutron stars. In order to understand the evolution of hot stars, we must be able to describe their stellar winds. Hot stars are capable of producing winds much stronger than the solar wind, leading to mass-loss rates on the order of 10^{-6} solar masses per year. Over the course of its lifetime, a star can thus loose a significant fraction of its total mass. As the ultimate fate of a star depends on its mass at the end of its lifetime, knowing the mass-loss rates of early-type stars allows us to predict whether they will end up as black holes or neutron stars.

Massive stars drive their winds through radiation pressure, transferring the net outward momentum of their photons to material on the surface of the star through scattering and absorption. Consequently, the more luminous a star is, the stronger the wind it can support. This wind-driving mechanism is inherently unstable. For material moving at the same velocity away from the star, absorption occurs at the same Doppler shift, and thus the material "shadows" itself, preventing further absorption. However, if some material begins to move faster than the surrounding matter, it can then absorb light at bluer wavelengths than the surrounding material, and thus accelerates. The faster this material moves in comparison to the surrounding material, the further out of the Doppler shadow it moves, and the more it accelerates. Eventually, the fast-moving material rams into slow-moving material, producing a shock. The high temperatures at these shock fronts allow for atoms to become highly ionized through collisions. The hydrogen- and helium-like ions produced then emit in the x-ray regime.

By studying these x-rays, we can deduce information about the properties of the wind. Namely, we can compare the high-resolution data acquired with space telescopes like *Chandra* to models of x-ray production based on our pre-existing knowledge of the wind. These models predict broad lines due to x-ray production in the fast-moving portions of the wind and asymmetrical lines due to the preferential absorption of red-shifted photons from the back of the wind.

X-ray Line Profile Model

Figure 1: Wavelength dependence of the opacity.



The x-ray line profile model is fully described in Owocki & Cohen, 2001. The model assumes a smooth, spherically symmetric wind with a velocity field given by

$$v = v_\infty \left(1 - R_* / r\right)^\beta . \qquad (1)$$

β and the terminal velocity, v_∞, can be determined from UV and optical diagnostics and have typical values of 1 and 2000 km s^{-1}, respectively. The x-ray emitting material, which makes up only a small fraction of the wind, is distributed evenly throughout the cooler, absorbing material and follows the same velocity law.

Red-shifted photons from the back of the wind must pass through more wind material to reach us than the blue-shifted photons in the front of the wind. Red light is thus preferentially absorbed, and the resulting emission line profile has a characteristic asymmetric shape. The asymmetry is parameterized by the fiducial optical depth τ_*, which is related to the wind's fundamental parameters by

$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty} . \qquad (2)$$

Here, κ is the wavelength-dependent opacity (Figure 1), and $\dot{M}$ is the mass-loss rate. As can be seen in Figure 2, higher values of τ_* correlate with more absorption and more asymmetry.

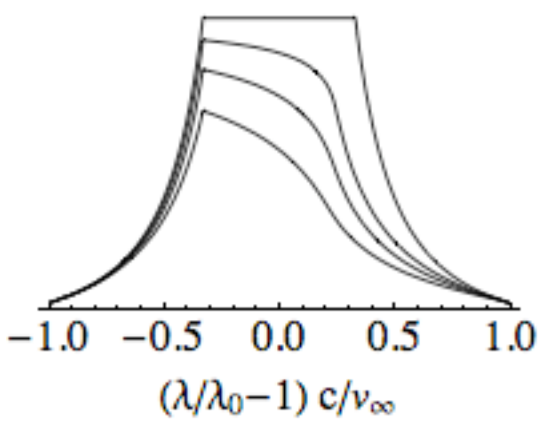


Figure 2: A series of line profile models with τ_* values increasing from 0 (top model) to 0.5 (bottom model).

By fitting the line profile model to the emission lines in a spectrum, we can obtain values of τ_* at several different wavelengths. As R_* and v_∞ are known and the wavelength dependence of the opacity can be modeled, we can then fit Equation 2 to the τ_* values to find the best-fit mass-loss rate.

Spectral Fitting

All x-ray spectra were obtained from *Chandra*'s archive. Here, we present data from four stars: the O3 supergiant HD 93129 A, the O4 main sequence star 9 Sgr, the O7.5 giant ξ Per, and the O9.5 supergiant ζ Ori. Fitting was done with an implementation of the line profile model in the *Chandra* analysis package *XSPEC*. Fits to the data were in general statistically good, with most having rejection probabilities of less than 90 percent. As expected, the more luminous stars had higher τ_* values at a given wavelength (Figure 3). After τ_* values were obtained for the strongest lines in a given spectrum, we fit Equation 2 to the data points in *Mathematica*, weighting each point by the inverse square of its error (Figure 4).

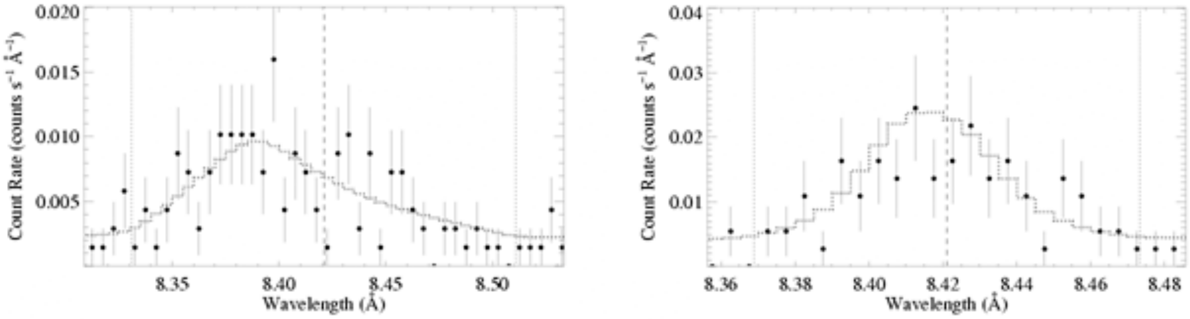


Figure 3: Fit to the Mg XII line at 8.421 angstroms in both HD 93129A (left) and ζ Ori (right). For HD 93129A, the fit gives $\tau_* = 2.44 \pm^{1.44}_{1.30}$. For ζ Ori, $\tau_* = 0.08 \pm^{0.24}_{0.08}$.

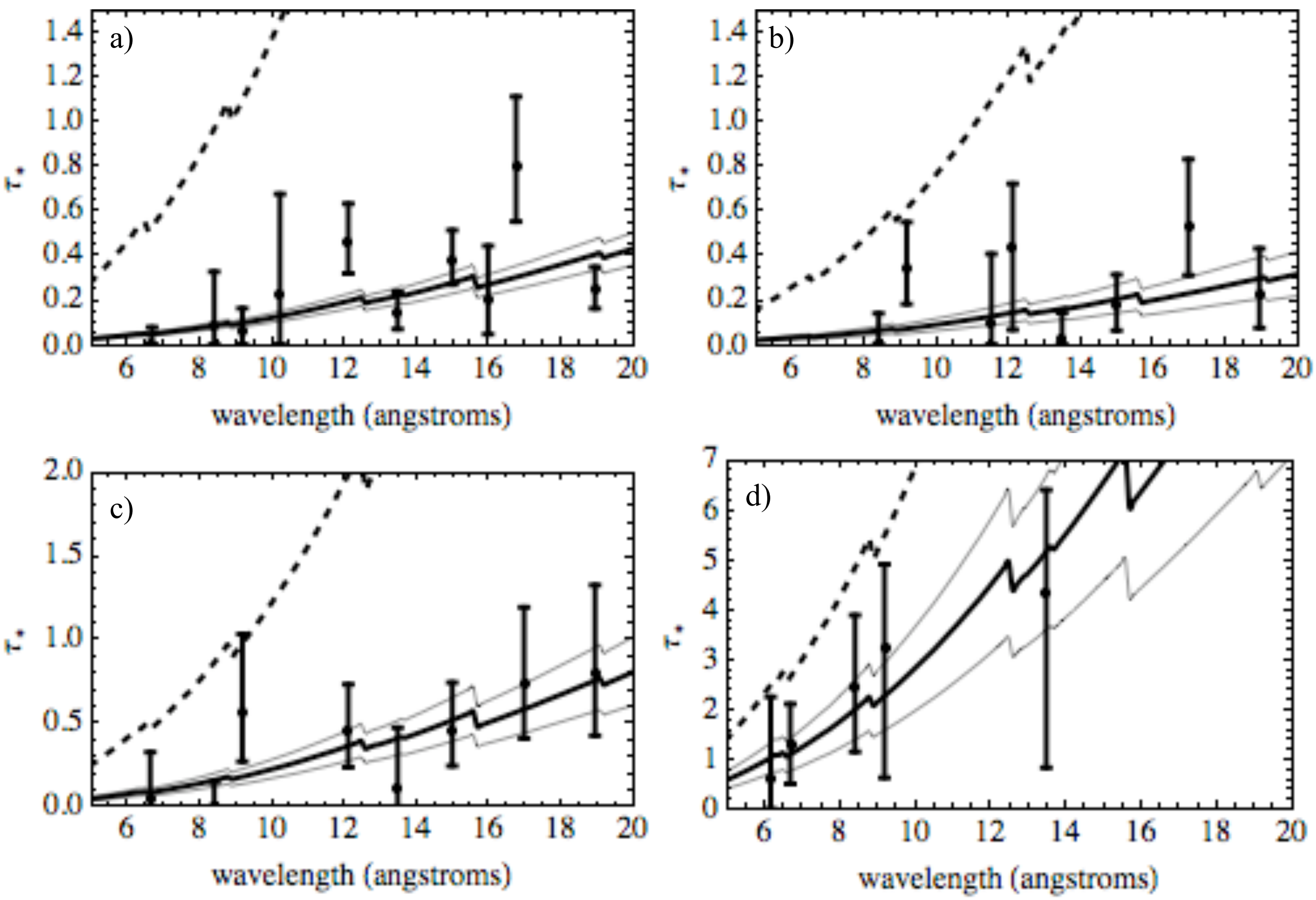


Figure 4: Mass-loss rate fits for a) ζ Ori, b) ξ Per, c) 9 Sgr, and d) HD 93129. The best-fit mass-loss rate along with its 68% error bounds are represented by solid lines, while τ_* values for literature mass-loss rates are represented by dashed lines. Results of fitting are listed in Table 1.

Star	Spectral Type	X-ray Mass-loss Rate ($10^{-6} M_\odot yr^{-1}$)	Literature Mass-loss Rate ($10^{-6} M_\odot yr^{-1}$)
ζ Ori	O9.7	0.22 ± 0.04	2.51 (1)
ξ Per	O9.5	0.12 ± 0.04	1.07 (2)
9 Sgr	O4	0.38 ± 0.10	2.09 (3)
HD 93129 A	O3	9.1 ± 2.7	22 (4)

Table 1: Comparison of mass-loss rate values from this paper and others. References: 1) Lamers & Leitherer, 1993. 2) Repolust et al., 2004. 3) Fullerton et al., 2006. 4) Puls et al., 1996.

Results

For the later stars in our data set, ζ Ori and ξ Per, we find mass-loss rate reductions of an order of magnitude. For the earlier stars in our data set, 9 Sgr and HD 93129 A, we find that the mass-loss rates are reduced by factors of 5 and 2, respectively (Table 1). While a 10-fold reduction is difficult to explain, recent reassessment of UV and visual mass-loss rate diagnostics has resulted in a downward revision of mass-loss rates. These diagnostics, which depend on the square of the wind density, are sensitive to the effects of clumping. The x-ray line profile model, on the other hand, is not sensitive to optically thin clumping (so-called "microclumping"). In this context, the moderate mass-loss rate reductions indicated by 9 Sgr and HD 93129 A are reasonable and support the presence of microclumping in these winds.

Acknowledgments

Thanks to my advisor David Cohen for his inspiration and guidance, and to the Keck Northeast Astronomy Consortium for the opportunity to present my work.

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