Photoelectric absorption as an x-ray spectral diagnostic of massive star winds

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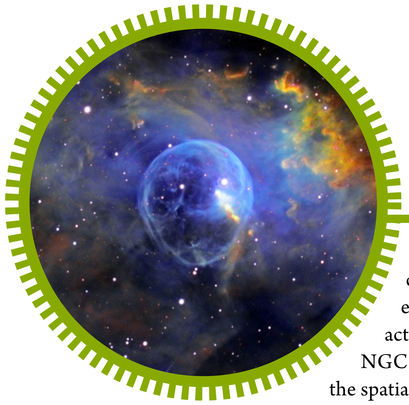
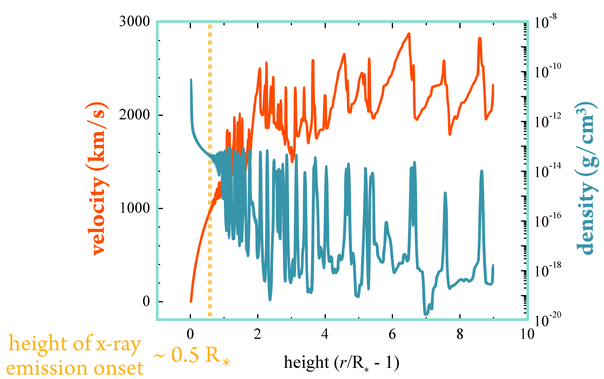


Massive star winds

The winds of massive stars deposit chemically enriched matter as well as energy and momentum into their galactic environment (wind-blown bubble NGC 7635 at left). The x-rays produced in the spatially unresolved circumstellar environment are a sensitive diagnostic of the mass-loss rate, the key measureable parameter that determines the influence of stellar winds. Typical mass-loss rates of O stars are $\dot{M} \sim 10^{-6}\ M_{\odot}$/yr.

X-ray production

Instabilities lead to shock-heating of the wind. These shocked regions, which make up a small fraction of the total wind mass, reach temperatures between 10^6 and 10^7 K. In the simulation shown to the left, shocks start developing about half a stellar radius above the surface of the star.

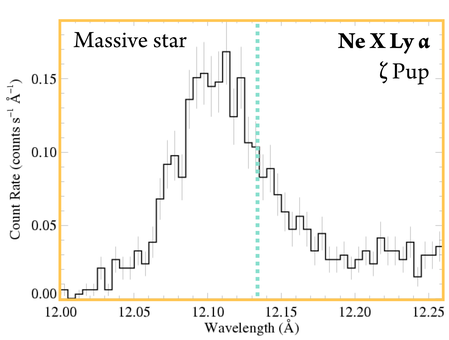


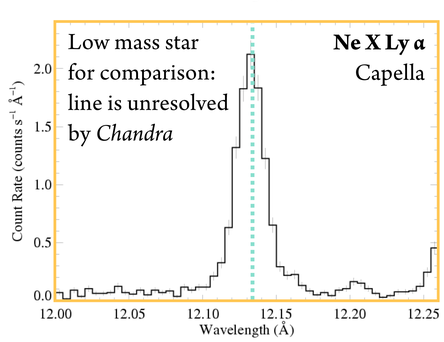
Theoretical predictions

1. In the shock regions, highly ionized atoms produce thermal x-ray emission lines.

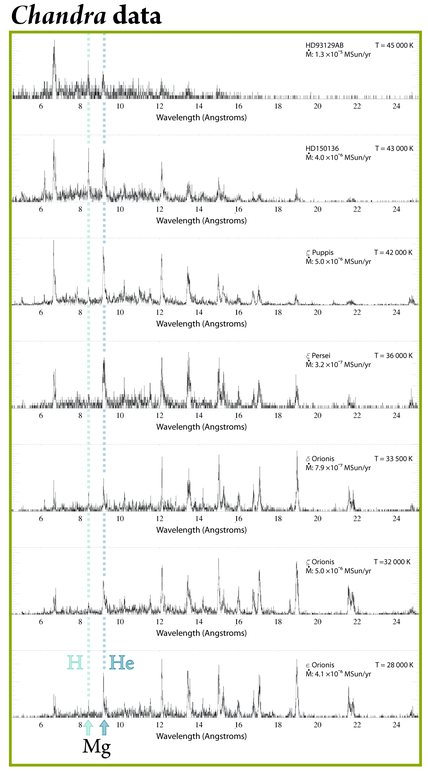
2. Production in the fast-moving wind results in Doppler-broadened lines.

3. The cool material in the wind absorbs x-rays. We should find evidence of this absorption in both the overall spectrum and in the shape of individual line profiles.

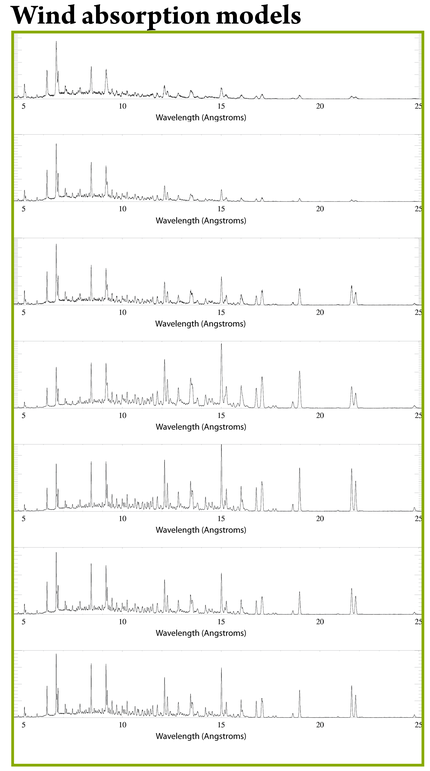




Chandra data



Wind absorption models



Chandra spectra of massive stars

High-resolution x-ray spectra of massive stars show a trend in spectral hardness with stellar surface temperature (and mass and luminosity): above left, hottest stars at top have hardest spectra.

Is this trend due to the emission temperature of shock-heated plasma?

Or, is it due to increasing **wind absorption** of x-rays for hotter stars that have stronger winds?

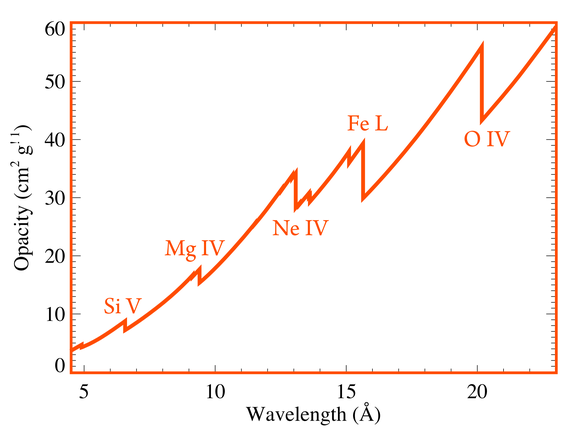
We have developed a radiation transport model of thermal x-ray emission from plasma embedded within an extended stellar wind. Preliminary models that all assume the same intrinsic spectrum but with differing amounts of wind attenuation (shown in the right panel) reproduce the observed hardness trend. There may still be some trend in the temperature distribution, however – ratios of H/He-like lines are the key to determining this (see the highlighted Mg XII/XI lines in the left panel).

Atomic opacity

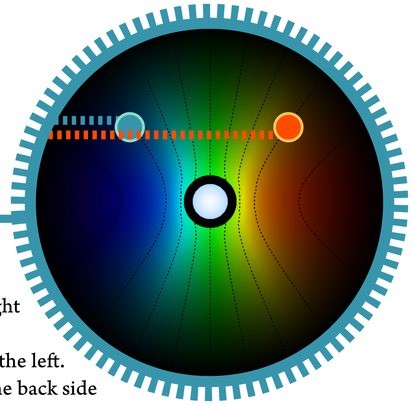
The opacity of the (cold, unshocked component of the) wind is due to K-shell photoionization of low-Z elements: C, N, O, Ne, Mg and the L-shell of Fe and Ni in a cosmic abundance mixture.

The opacity is greater at longer wavelengths: Wind absorption hardens the overall X-ray spectrum (figure at top of this column).

And this continuum opacity also skews the individual Doppler-broadened line profiles (explained in the right-hand column).



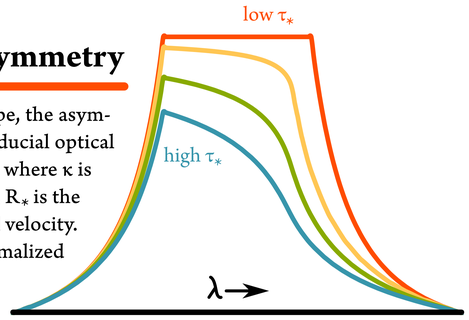
Wind geometry



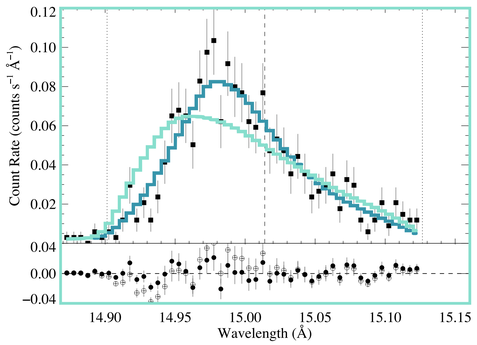
The shape of the individual x-ray emission lines is also governed by absorption. The diagram to the right shows contours of constant radial velocity as seen by an observer to the left. Red-shifted x-rays emitted from the back side of the wind must pass through more material than blue photons emitted from the front of the wind. Red photons are thus preferentially absorbed, leading to asymmetric lines.

Line asymmetry

In our model of the line profile shape, the asymmetry is parameterized by τ_*, the fiducial optical depth. τ_* is defined as $\kappa\dot{M}/4\pi R_* v_\infty$, where κ is the opacity, $\dot{M}$ is the mass-loss rate, R_* is the stellar radius, and v_∞ is the terminal velocity. Plotted to the right are four un-normalized models with different values of τ_*.



Fitting the data



The Fe XVII line at 15.014 angstroms in ζ Pup is shown with two models. The dark blue model represents the best fit and yields a τ_* value of 1.94. The fit also gives us the radius of x-ray emission onset, which is 0.55 stellar radii above the star's surface for this line. The light blue model represents a fit with a fixed τ_* value of 5.30 dictated by the mass-loss rate obtained from H-α diagnostics. The best-fit curve is clearly less shifted than predicted by the H-α mass-loss rate, indicating a lower mass-loss rate.

Mass-loss rate determination from global fit

The Fe XVII line is not the only line in ζ Pup's spectrum to show less asymmetry than the H-α mass-loss rate would require. Using the wavelength-dependent opacity, we can fit a single mass-loss rate to all lines in the spectrum. The dark blue curve shows the best-fit mass-loss rate of $3.5\times10^{-6}\ M_{\odot}$/yr and the dashed curve shows the H-α mass-loss rate of $8.3\times10^{-6}\ M_{\odot}$ /yr. We see that the H-α mass-loss rate is inconsistent with the data and that a lower mass-loss rate is preferred. In other stars, the best fit mass-loss rates are up to an order of magnitude lower than values obtained from other diagnostics.