The need for high-resolution soft x-ray spectroscopic capabilities for the study of massive stars

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Massive stars are thought to produce x-rays via shock-heating of their dense, very fast, radiation-driven stellar winds. The specifics of this theoretical picture are, however, not well understood and are consequently the subject of much interest and dispute (e.g. does coronal heating play a role? What is the fundamental nature of the wind-shock mechanism? Are the spectral signatures of transport through an optically thick wind telling us something about wind mass-loss rates and/or inhomogeneities?). Furthermore, it seems that in some massive stars - primarily young ones - x-ray production is related to large-scale magnetic fields. X-ray spectroscopy is an excellent means for investigating the various models of high-energy emission that have been proposed for massive stars, and these objects are some of the best test-beds for demonstrating the utility of high-resolution x-ray spectroscopy for studying outflows, interactions of central engines with circumstellar material, and other physical scenarios that are applicable to XRBs, AGNs, GRBs, and other more exotic and more distant objects.

The x-ray emission from massive stars is generally relatively soft, with some exceptions (related to the involvement of magnetic fields, it seems) optically thin and thermal. The He-like and H-like features of O, Ne, Mg, Si, and S, along with Fe L-shell lines are generally the strongest features in the spectra of massive stars. Only in a few cases (γ Cas[1], θ^1 Ori C[2]) is Fe K-shell emission seen. The key characteristic of massive star x-ray spectra are their broad line profiles, due to the kinematics of the emitting plasma, which is embedded in the fast (~ few 1000 km/s) winds of these objects. For most O supergiants, the HWHMs seen in Chandra and XMM grating spectra are roughly 1000 km/s, however, for some of the young, magnetized massive stars (θ^1 Ori C[2], τ Sco[3]) HWHMs are of order 200 km/s.

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[1] "High-Resolution *Chandra* Spectroscopy of γ Cassiopeia (B0.5e)," Smith, Cohen, Gu, Robinson, Evans, & Schran 2004, *Ap.J.*, 600, 972
[2] "*Chandra* HETGS Multi-phase Spectroscopy of the Young Magnetic O Star θ^1 Ori C," Gagne, Oksala, Cohen, Tonnesen, ud-Doula, Owocki, Townsend, & MacFarlane 2005, *Ap.J.*, 628, 986
[3] "*Chandra* Spectroscopy of τ Scorpii: A Narrow Lined Spectrum from a Hot Star," Cohen, de Messieres, MacFarlane, Miller, Cassinelli, Owocki, & Liedahl 2003, *Ap.J.*, 586, 495

The kinematic properties of the emitting plasma establishes the widths of the x-ray emission lines and influences their profile shapes. The profile shapes are also affected by radiation transport effects through the bulk (cold) stellar winds. By analyzing the profile shapes and the effects of continuum (bound-free) attenuation, information about the spatial distribution of the hot plasma can be derived. Thus, the spectrally resolved x-ray emission lines provide constraints on physical models of mechanical heating in massive stars. The dissipation of mechanical energy in unstable outflows, the role of magnetized winds, and the possibility of magnetic reconnection heating in circumstellar matter can all be studied via x-ray spectroscopy of massive stars, with the results perhaps having much broader applicability to other objects with energetic outflows.

What can be accomplished with higher resolution soft-x-ray spectroscopy (on an observatory with good throughput)?

(1) The *Chandra* grating spectra of O supergiants have roughly 10 to 15 resolution elements across the broadest spectral lines:

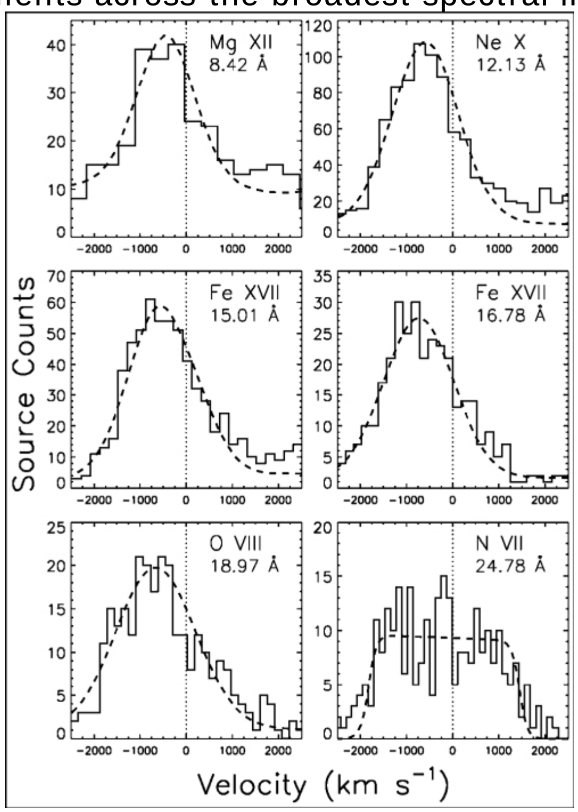

Fig. 1: A suite of emission lines in ζ Pup (O4 If) observed with the *Chandra* HETGS (from Cassinelli et al. 2001, *ApJ*, 554, L55). Does the N VII line have a significantly different shape than the other lines, formed at higher temperatures? Are the deviations from Gaussian profile shapes significant?

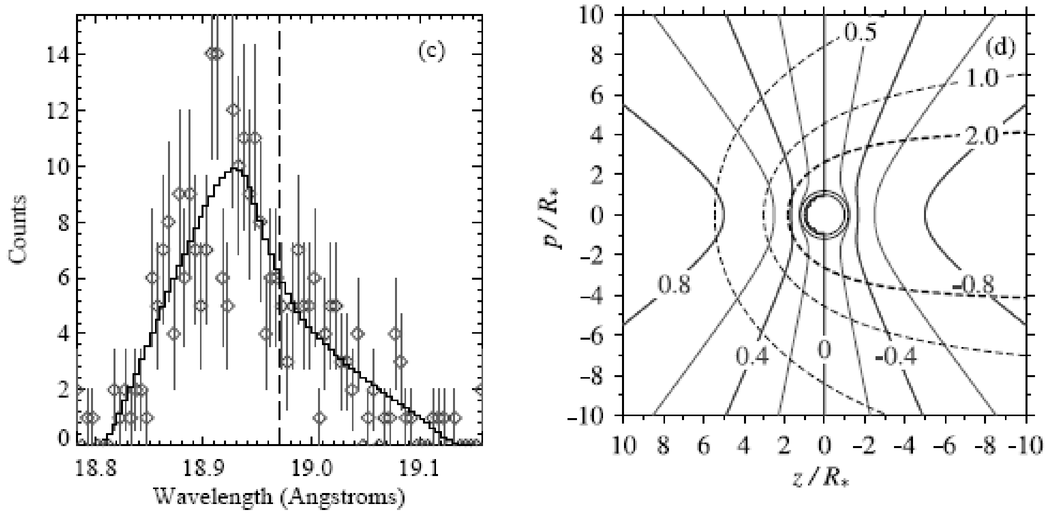

Fig. 2: The O Ly-alpha line in ζ Pup (left) exhibits signatures of wind kinematics plus attenuation in accord with a simple model of emission in a spherically symmetric, expanding, emitting and absorbing wind (right). To fit the profile shape, however, the mass-loss rate must be almost an order of magnitude less than the values found in the literature. From Kramer, Cohen, & Owocki 2003, ApJ, 592, 532.

More detailed information about hot plasma kinematics can be obtained with higher resolution spectra. Specifically, information has recently emerged that the relatively subtle asymmetries seen in the x-ray emission lines of O supergiants may be due to lower-than-expected mass-loss rates[4] or they may be due to clumping in the bulk, x-ray absorbing components of these winds[5]. The differences between the spectral signatures from these two scenarios will require spectral resolutions of several thousand to differentiate.

[4] "X-ray Emission Line Profile Modeling of O Stars: Fitting a Spherically-Symmetric Analytic Wind-Shock Model to the *Chandra* Spectrum of ζ Puppis," Kramer, Cohen, & Owocki 2003, *Ap.J.*, 592, 532; see also Bouret, Lanz, & Hillier 2005, *A&A*, 438, 301 and also Fullerton, Mass, & Prinja 2006, *ApJ*, 637, 1025 for independent evidence of mass-loss rate overestimates.

[5] Oskinova, Feldmeier, & Hamann 2005, *astro-ph/110190* and Owocki & Cohen 2006, *astro-ph/0602054*.

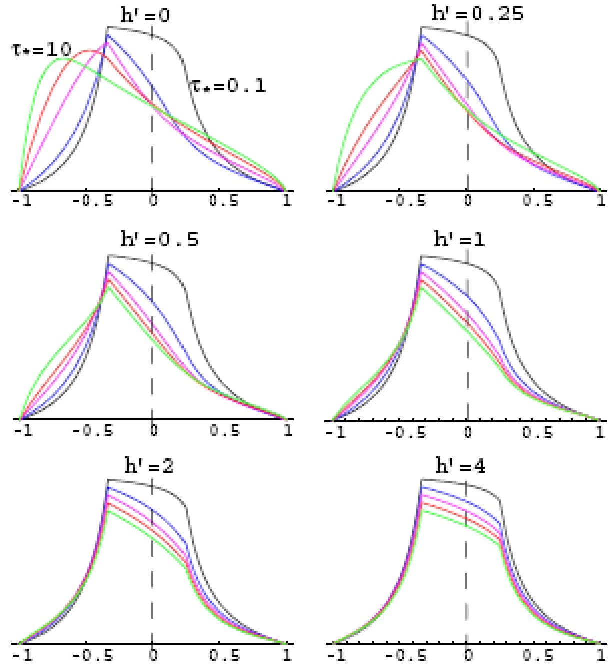

FIG. 3.— X-ray line profiles vs. scaled wavelength $x \equiv (\lambda/\lambda_o - 1)c/v_\infty$, overplotted in each panel for optical depth parameters $\tau_* = 0.1$, 1, 3, 5, and 10 (black, blue, violet, red, green), and normalized to have peaks decrease by 5% for each step in τ_*. The panels compare results for various porosity scale factors $h' = 0$, 0.25, 0.5, 1, 2, and 4, ordered from upper left to lower right. The vertical dashed line marks the line center. Note that porosity can make otherwise optically thick cases (i.e. $\tau_* = 3, 5, 10$) have nearly symmetric profiles, but only with quite large porosity scale factors, $h' > 1$, as seen in the lowermost panels.

Fig. 3: The effects of wind continuum opacity (varying, according to colored lines within each panel) vs. the effects of clumping/porosity (varying from one panel to the next) are similar in that lower mass-loss rates and associated reduction in optical depths make emission lines more symmetric, however the effective reduction in opacity due to transport through a porous medium also makes lines more symmetric, but in ways that have subtle differences. Note that the x-axes typically span 3000 km/s. So differentiating these two effects will require resolutions of several 1000. Taken from Owocki & Cohen 2006, *astro-ph/0602054*.

Additionally, spectral substructure (analogous to DACs in UV absorption lines and “moving bumps” in WR wind optical emission lines) and time variability in emission line morphologies will require a combination of high throughput and high resolution (at least R=2000, but probably more).

(2) He-like forbidden-to-intercombination line ratios provide information about the location of the x-ray emitting plasma, with respect to the photosphere, in massive stars, due to the very strong

UV fluxes from these stars (and the consequent 2s ^{3}S – 2p ^{3}P photoexcitation). The blending of wind-broadened forbidden and intercombination components (and the possible presence of satellite lines) makes the analysis of these complexes quite difficult at the resolution of *Chandra* and *XMM*.

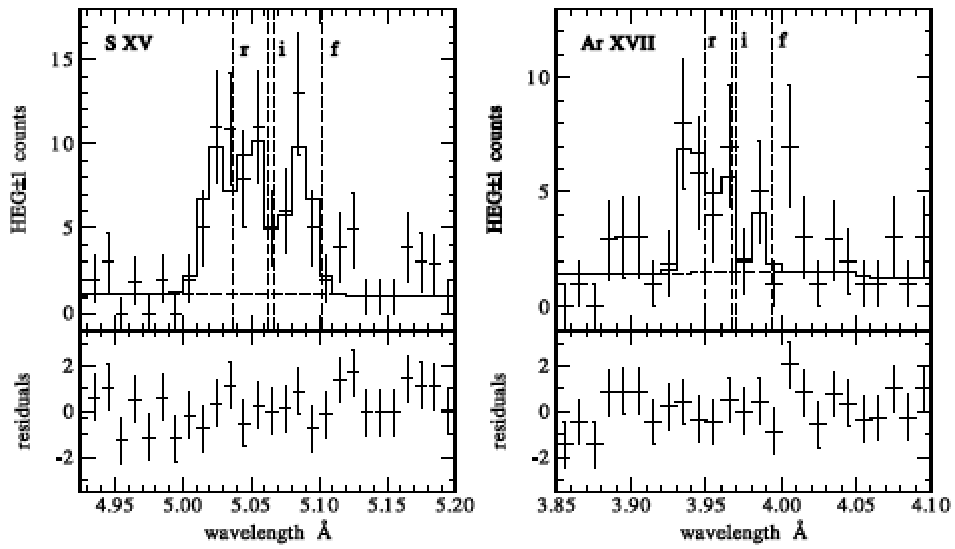

Fig. 4: The most interesting, and ostensibly surprising f/i ratio results in O stars come from complexes that have both poor S/N and significant problems with blending. Data from Cyg OB2 #8; figure taken from Waldron et al., *ApJ*, 616, 542. Higher resolution, coupled with better throughput, will allow for much more reliable measurements of line ratios.

(3) The younger, magnetized massive stars have narrower (but still resolved at the resolution of the *Chandra* gratings) emission lines. These sources also have harder x-ray emission than is seen in the O supergiants. A hybrid magnetic-wind model (the MCWS model) has been quite successful at explaining the emission properties, in terms of magnetic channeling of the wind[6]. Assessing the kinematics of these confined winds as well as the rotational modulation, will require spectral resolution of several thousand, as the emission lines from these stars have characteristic widths of only a few 100 km/s. A series of *Chandra* grating observations of the oblique magnetic rotator θ^1 Ori C shows a hint of systematic centroid shifts and subtle variations in profile shapes with rotation period.

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[6] Babel & Montmerle 1997, *ApJ*, 485, L29; and ud-Doula & Owocki 2002, *ApJ*, 576, 413; and Gagné et al. 2005, *ApJ*, 628, 986.

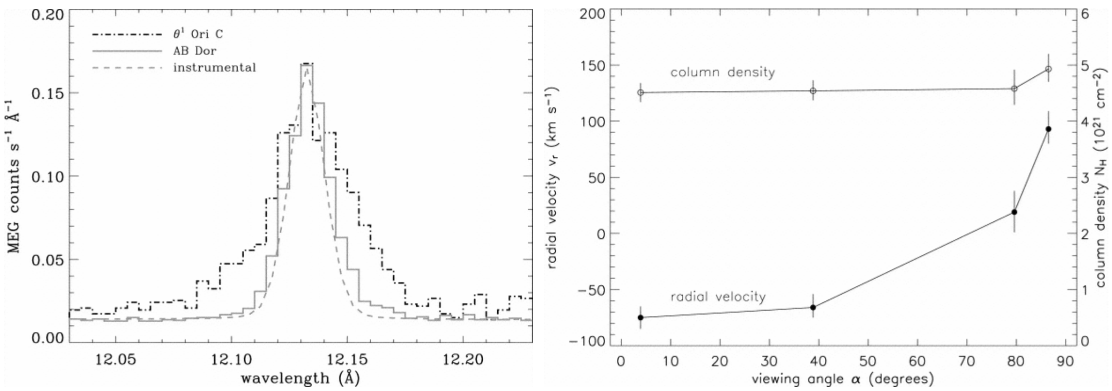

Fig. 5: The marginally broadened Ne X emission line in the magnetic wind source θ^1 Ori C, as measured with the *Chandra* HETGS (left) and evidence for viewing-angle dependence of the emission line centroids in the same data (lower line, right) (from Gagne et al. 2005, *ApJ*, 628, 986).

See also numerical MHD simulations of this star and its x-ray emission properties:

http://www.sccs.swarthmore.edu/users/07/sstvinc2/research/movies.html

http://shayol.bartol.udel.edu/~rhdt/t1oc/

(4) Finally, reconnection heating and the related impulsive x-ray emission have recently been predicted[7] for magnetically strong Bp stars like σ Ori E (B2p), which has a weak wind, a strong (measured) magnetic field, and ubiquitous hard x-ray flaring. If the x-ray flares are due to centrifugal breakout, as has recently been proposed, then kinematic/Doppler signatures should be detectable with spectral resolutions in excess of $R=1000$.

[7] Townsend, Owocki, & Groote 2005, *ApJ*, 630, L81; ud-Doula, Townsend, & Owocki 2006, *astro-ph/0601193*.

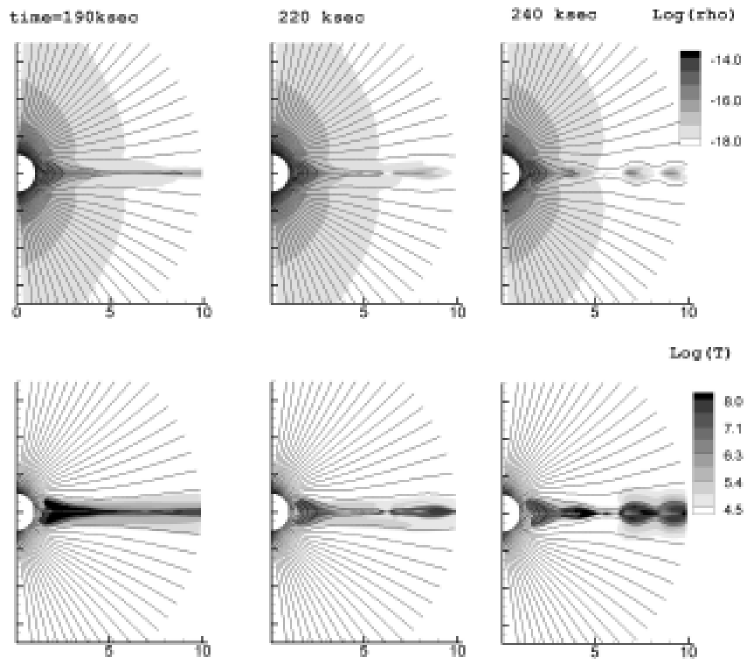

Fig. 6: Sequence of snapshots from an MHD simulation of centrifugal breakout in the magnetosphere of σ Ori E (from ud-Doula, Townsend, & Owocki 2006, *astro-ph/0601193*).