HOW MUCH OF THE TREND IN O STAR X-RAY SPECTRAL HARDNESS IS DUE TO WIND ABSORPTION?

The strong soft X-ray emission from normal[1] massive stars is assumed to arise in wind-shocked plasma generated by the line-driven instability [1]. *Chandra* grating spectra have confirmed this general picture via the observation of significantly Doppler-broadened emission lines [2]. But contrary to expectations, *Chandra* grating spectroscopy also has revealed a surprising trend of X-ray spectral hardness with spectral subtype (early O stars having harder X-ray spectra than late O stars; see the left panel of Fig. 1). This discovery [3,4] was unexpected, and the initial suggestion – that this hardness trend represents an ionization, and therefore a temperature, effect – is not anticipated by wind-shock theory [5] and would require a significant shift in our view of X-ray production in O star winds. The *Chandra* grating observations of O stars are rich with information, and can uniquely address the question of whether earlier O stars really do have hotter X-ray emitting plasma, and – crucially – the extent to which the observed trend is actually governed by wind absorption.

We have developed a radiative transfer model for X-ray emission and absorption in a stellar wind, and preliminary indications (right panel of Fig. 1) are that wind absorption may explain much of the observed trend in spectral hardness. The key ingredient of this model is the spatial distribution of the emitting plasma, which is mixed throughout the wind above some onset radius. This makes the wind absorption a weaker function of optical depth than the usual $e^{-\tau}$ from an absorbing slab above an emitting region. We compare the transmission in this spatially distributed model to that in the traditional exponential attenuation model in Fig. 2.

Using this physical model of X-ray radiation transport through a stellar wind[2], we implemented a custom model in XSPEC (which we call *windtabs*). The column density is the lone free parameter of this model (although different atomic opacity models can be used). We calculated a series of *apec* emission[3] with *windtabs* (and interstellar) absorption models, each with the wind column density appropriate to one of the seven stars from the archives. We show these models in the right-hand panel of Fig. 1, opposite the corresponding star's spectrum from the *Chandra* archive. We stress that the *apec* emission component is exactly the same for each model, only the absorption varies. This sequence of models reproduces very well the qualitative trend seen in the data.

Despite the lack of adjustable parameters, the agreement between model and data seems good, but there certainly may still be a temperature or ionization trend. As pointed out by Walborn [3,4], such trends should appear robustly in ratios of emission lines from adjacent ionization states (He-like and H-like, primarily) of the same element. These features are relatively close to each other in the spectra, and thus should suffer little differential absorption. We have begun to evaluate these line ratios by fitting Gaussian emission line models to pairs of H-like and He-like lines in these star's grating spectra. Some residual ionization trend with spectral subtype does appear to be present.

So, there is now an obvious need to test models of wind emission and absorption quantitatively and rigorously in order to determine the relative contributions of these two effects. We therefore propose to quantitatively analyze the archival spectra of all normal O and early B stars with

[1] By "normal" we mean that the X-ray emission is not obviously due to wind-wind interactions in a close, massive binary, nor is it due to strong magnetic fields.

[2] Which is given by numerically integrating equations 1 and 4 in [6], ignoring the Doppler shift of the effective optical depth and instead using the APEC emission model for the wavelength-dependent emissivity. We note that we have recently used the original version of this formalism – describing individual X-ray line profile shapes – to measure the mass-loss rate of ζ Pup via the trend in its X-ray line profiles [7].

[3] Astrophysical Plasma Emission Code [8]. The model we used has five temperature components, to approximate a continuous temperature distribution. We broaden the lines in each model spectrum using the *gsmooth* model in XSPEC.

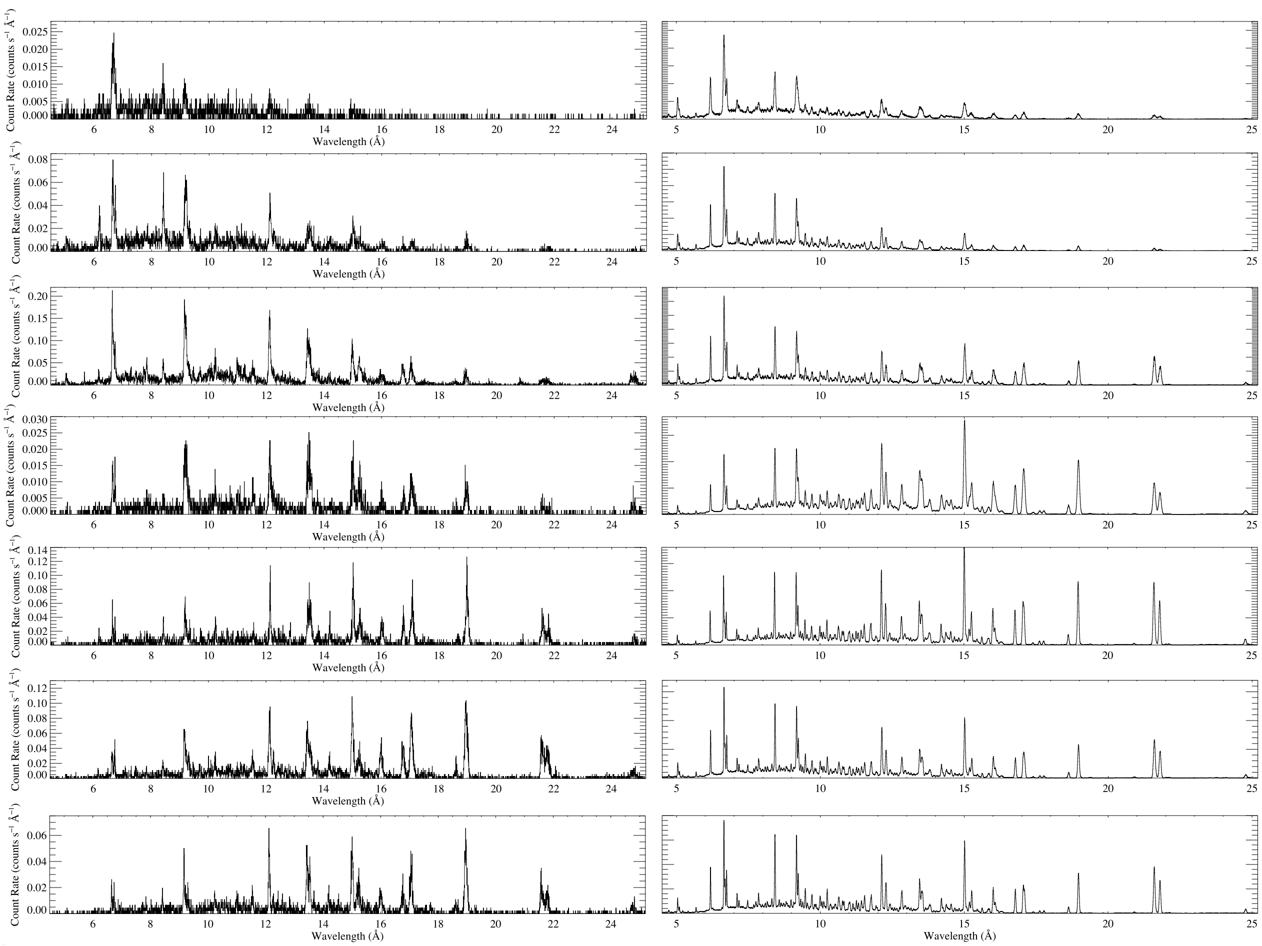

Figure 1: Measured MEG spectra of six O (and one B0) giants and supergiants from the *Chandra* archive (left). From the top, these stars are HD 93129 (O2.5), HD 150136 (O3.5), ζ Pup (O4), ξ Per (O7.5), δ Ori (O9.5), ζ Ori (O9.7), and ϵ Ori (B0). These are the same stars for which Walborn (2006, 2008) identified the hardness trend. In the right-hand panel, we show the same emission model in each panel but combined with the *windtabs* wind absorption model, assuming the literature mass-loss rate for each star.

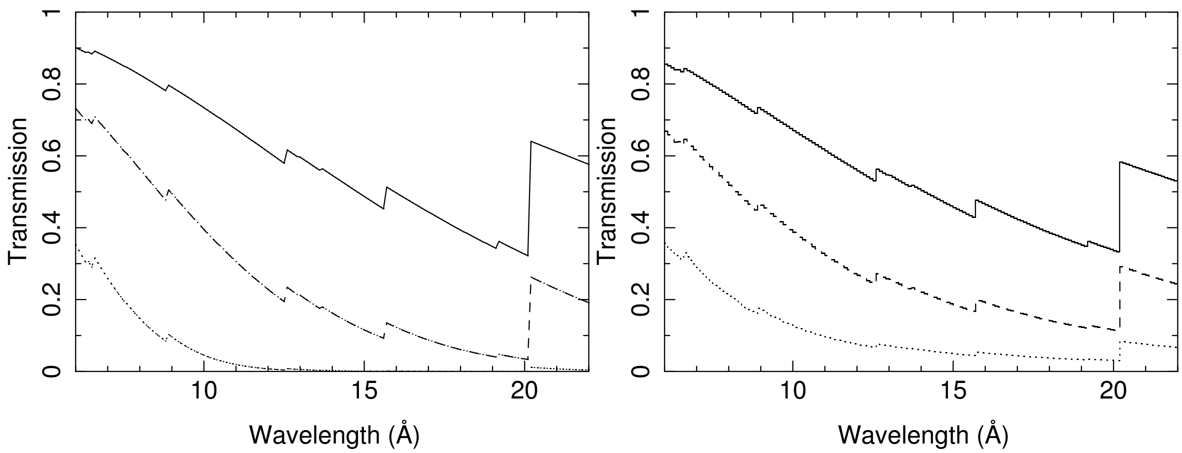

Figure 2: Models of wind transmission (fraction of generated X-ray emission that is emergent from the wind) assuming canonical $I/I_o = e^{-\tau}$ slab absorption (left) and with the *windtabs* distributed emission model (right). For typical values of the wind terminal velocity, stellar radius, and wavelength-dependent opacity, the three curves in each panel correspond to mass-loss rates of 1, 3, and 10 $\times 10^{-6}$ $M_{\odot}$ yr^{-1} (top to bottom). The difference between the two panels is in the assumed spatial distribution of the emitting plasma. For the left-hand panel, the emitting plasma is entirely below the absorbing wind, and so the transmission goes as $1 - e^{-\tau}$. But for the models in the right-hand panel, the emitting plasma is smoothly distributed throughout the wind – in other words, it is mixed in with the absorbing medium, which makes the transmission a less steep function of optical depth. Note that the transmission decreases more gradually as one looks to higher mass-loss rates for the *windtabs* models. The transmission also changes more gradually for a given mass-loss rate as one looks toward longer wavelengths (where the atomic opacity is larger). The opacity used in these models is due to photoelectric absorption in the cool component of the wind, based on detailed modeling of the wind ionization with CMFGEN, along with abundance constraints from optical spectra, and the atomic cross sections of Verner and Yakovlev (1995).

broad lines in the *Chandra* archive[4]. We will use a multi-pronged approach to assess the relative importance of ionization and wind absorption, described below.

What we propose to do: As a proof-of-principle, we have simulated spectra using a universal *apec* emission model along with our custom model of wind attenuation, as discussed above (and shown on the right side of Fig. 1). Now we need to fit these models (including line broadening, via the *bapec* variant of *apec*) to the *Chandra* grating spectra. From this, we will derive best-fit wind column densities (and formal confidence limits on them). We suspect that we will find reductions in the mass-loss rates compared to the traditional values[5]. This would provide confirmation of recent results from X-ray line profiles [7], as well as from UV modeling [9,10] and joint H-alpha, IR, and radio modeling [11]. The spectral fitting will also enable us to constrain the emission temperature

[4]This includes the seven giants and supergiants shown in the left panel of Fig. 1 and also seven main sequence OB stars: HD 93250 (O3.5), 9 Sgr (O4), HD 206267 (O6.5), 15 Mon (O7), ι Ori (O9), σ Ori AB (O9.5), and β Cru (B0.5). These are the stars evaluated by Walborn in his original study. We note that two of these second set of seven stars are classified as giants, and that β Cru's emission lines are not significantly wind broadened, but we feel that we should analyze the same set of stars with which the initial discovery was made.

[5]We note that the late O supergiants' measured spectra do not soften quite as much as the corresponding models do. This implies that the mass-loss rates assumed for the models are too high.

distributions of the *apec* model and put formal uncertainties on it for each star. In this way, we will quantify the significance of the temperature trend originally postulated to explain the hardness trend seen in the data, but accounting properly for the dominant wind attenuation effect.

We will also exhaustively derive line intensity ratios from careful statistical fitting of individual emission lines and emission line complexes. This will provide a second means of testing the idea that the observed hardness trend is a result of a correlation in plasma temperature and ionization with spectral subtype. We note that for some line pairs in stars with quite dense winds (like the silicon lines in HD 93129), the differential wind attenuation between the wavelengths of the two lines is not negligible. We will model this effect when it promises to be significant.

After performing the global spectral modeling with *windtabs* and the individual line intensity fitting and analysis, as described above, to the sample of giants and supergiants we show in Fig. 1, we will apply the same sequence of analysis techniques to the seven normal main sequence OB stars with grating spectra in the *Chandra* archive (these are listed in footnote 4).

In summary: By accurately modeling the X-ray transport through the dense winds of O stars, we will see if we can reproduce the hardness trend seen in the *Chandra* grating spectra of these objects. We can use these models to constrain the mass-loss rates of O stars, which is a problem of significant current interest. And we can determine the extent to which there is a residual trend for earlier type O stars to have higher X-ray temperatures. This trend is not predicted by wind-shock theory, and if real, would pose a significant challenge to the theory.

Work plan and budget: Reduction of the data (14 stars' grating spectra, with several objects having multiple observations and/or crowded fields) will be carried out by Cohen and Gagné in consultation with Leutenegger. Those co-Is will also update the implementation of the *windtabs* model in XSPEC, incorporating customized wind opacity models for each star, and perform the statistical model fitting. Zsargó will model the wind ionization and opacity and constrain these models by comparisons with optical and UV data. Owocki will model and interpret both the wind absorption and the temperature trends in terms of wind-shock theory. Funding for five person months ($85K), two undergraduate students ($8K), and travel and publication costs ($5K) will be requested, for a total of $98K.

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DAVID H. COHEN: PREVIOUS CHANDRA PROJECTS (year in parentheses denotes graduating class of undergraduate co-author)

AO1 - τ Sco (PI) - publication: Cohen, de Messieres ('04), MacFarlane, Miller, Cassinelli, Owocki, & Liedahl, “Chandra Spectroscopy of τ Scorpii: A Narrow Lined Spectrum from a Hot Star," 2003, *Ap.J.*, 586, 495

A01 - ζ Pup and δ Ori (co-I) - publications: 1. Cassinelli, Miller, Waldron, MacFarlane, & Cohen, “Chandra Detection of Doppler Shifted X-ray Line Profiles from the Wind of ζ Puppis (O4f)," 2001, *Ap.J.L.*, 554, L55; 2. Miller, Cassinelli, Waldron, MacFarlane, & Cohen, “New Challenges for Wind Shock Models: The Chandra Spectrum of the Hot Star δ Orionis," 2002, *Ap.J.*, 577, 951; 3. Kramer ('03), Tonnesen ('03), Cohen, Owocki, ud-Doula, & MacFarlane, “X-ray Emission Line Profile Modeling of Hot Stars," 2003, *Rev. Sci. Inst.*, 74, 1966; 4. Kramer ('03), Cohen & Owocki, “X-ray Emission Line Profile Modeling of O Stars: Fitting a Spherically-Symmetric Analytic Wind-Shock Model to the Chandra Spectrum of ζ Puppis," 2003, *Ap.J.*, 592, 532

AO2 - γ Cas (co-I) - publication: Smith, Cohen, Gu, Robinson, Evans, & Schran, “High-Resolution Chandra Spectroscopy of γ Cassiopeia (B0.5e)," 2004, *Ap.J.*, 600, 972

AO3 - θ^1 Ori C (co-I) - publication: Gagne, Oksala, Cohen, Tonnesen, ud-Doula, Owocki, Townsend, & MacFarlane, “Chandra HETGS Multi-phase Spectroscopy of the Young Magnetic O star θ^1 Ori C," 2005, *Ap.J.*, 628, 986

AO3 - β Cru (PI) – publication: Cohen, Kuhn (’07), Gagne, Jensen, & Miller, “Chandra Spectroscopy of the Hot Star β Crucis and the Discovery of a Pre-Main-Sequence Companion,” 2008, *MNRAS*, 386, 1855

AO4 - DoAr 21 (co-I) - manuscript in preparation for submission to *Ap.J.*, AAS presentation available at: astro.swarthmore.edu/~cohen/projects/doar21/DoAr21 AAS2005.jpg

AO6 - archive (PI) - publications: 1. Owocki & Cohen, “The Effects of Porosity on X-ray Emission Line Profiles from Hot-Star Winds," 2006, *Ap.J.*, 684, 565; 2. Cohen, Leutenegger, Grizzard (’06), Reed (’05), Kramer (’03), & Owocki, “Wind Signatures in the X-ray Emission Line Profiles of the Late O Supergiant ζ Orionis," 2006, *MNRAS*, 368, 1905

AO6 - theory (co-I) - publications: 1. Gagne, Oksala, Cohen, Tonnesen, ud-Doula, Owocki, Townsend, & MacFarlane, “Chandra HETGS Multi-phase Spectroscopy of the Young Magnetic O star θ^1 Ori C," 2005, *Ap.J.*, 628, 986; 2. ud-Doula, Townsend, & Owocki, “Centrifugal Breakout of Magnetically Confined Line-Driven Stellar Winds," 2007, *Ap.J.L.*, 640, L191

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DAVID H. COHEN: biographical sketch

EDUCATION

University of Wisconsin-Madison Ph.D. in Astronomy, 1996, "High-Energy Emission from B Stars and Its Relationship to Stellar Winds," under the direction of Prof. Joseph Cassinelli

Harvard College A.B. in Astronomy and Astrophysics, *magna cum laude*, 1991, senior honors thesis, "Disentangling Double-Line Spectroscopic Binaries," under the direction of Dr. David Latham

EMPLOYMENT

Associate Professor Swarthmore College, 2006–present

Assistant Professor Swarthmore College, 2000–2006

Research Scientist Bartol Research Institute, University of Delaware and Prism Computational Sciences 1998–2000

Post-doc, Assistant Scientist Fusion Technology Institute and Astronomy Department, University of Wisconsin-Madison, 1996–1998

RESEARCH INTERESTS

X-ray spectroscopy and **numerical modeling** of hot plasmas in laboratory and astrophysical settings

Stellar winds high-energy observations and analysis, collisional-radiative and hydrodynamic modeling, analytic modeling

X-ray/EUV astronomy spectral analysis, time-variability analysis, hot stars, young stars, interstellar medium

Laboratory astrophysics ionization/excitation kinematics modeling, spectroscopy, and experiment design of x-ray photoionized plasmas; plasmas heated by magnetic reconnection

Inertial confinement fusion experiment design and modeling—shock physics, ionization dynamics, and non-LTE physics

SELECTED PUBLICATIONS (more information at astro.swarthmore.edu/~cohen)

Cohen, Kuhn ('07), Gagne, Jensen, & Miller, "Chandra Spectroscopy of the Hot Star β Crucis and the Discovery of a Pre-Main-Sequence Companion," 2008, MNRAS, 386, 1855

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Owocki & Cohen, "X-ray Line Profiles from Parameterized Emission Within an Accelerating Stellar Wind," 2001, *Ap. J.*, 559, 1108