DERIVING EMISSION MEASURES AND MASS-LOSS RATES FROM *CHANDRA* GRATING SPECTRA OF OB STARS

1 Introduction

Following the surprising discovery by *Einstein* of strong, soft X-rays from single O stars [1], data from subsequent missions – and most notably the grating spectra from *Chandra* – have provided strong evidence that these X-rays arise in *Embedded Wind Shocks* (EWS), which are most likely associated with intrinsic instabilities in the radiative driving of their dense stellar winds [2,3]. For example, wind Doppler broadening of X-ray *emission* from EWS provides a natural explanation for the observed breadth (~ 1000 km s^{-1}) of individual emission lines (e.g., [4]); and the larger wind *absorption* from the back vs. front hemisphere leads naturally to the observed blueward asymmetry and shifted peaks of these lines, which thus provide a key diagnostic of the wind column density [5,6,7].

However, the physical processes that produce the X-ray emitting plasma in O star winds are still not well understood. Recently, a strong challenge has been posed to wind-shock theory by the observed trend of X-ray spectral hardness with optical spectral subtype [8]. There is no theoretical expectation that effective temperature or spectral subtype should be correlated with the X-ray emitting plasma temperature or ionization state, and if it proves to be the case that there is a correlation, it would provide a most important observational clue about wind instabilities, shocks, and X-ray production mechanisms in massive, hot stars.

But an important point – and indeed a key theme of this proposal – is that proper consideration of such X-ray emission properties also demands an accurate account for the *absorption* effects of the wind. Moreover, the amount of absorption, via the mass-loss rate, *does* correlate with luminosity, and since absorption tends to harden X-ray spectra, it can, in principle, provide a natural explanation for the hardness trend with spectral subtype. Unfortunately, previous analyses (e.g., [8, 9, 10]) have largely cast the spectral properties and hardness of O-star X-rays simply in terms of the source emission, and have either ignored or considered only a cursory treatment of absorption, most typically lumping wind absorption together with interstellar absorption. Therefore, more than ten years after the launch of *Chandra*, we still do not have reliable information about the hot plasma temperature distribution (differential emission measure, or DEM) of the shock-heated winds of O stars.

As emphasized below (see §2 and Fig. 1), the embedded nature of X-rays from the EWS model means that the *internal* absorption by cooler material within the expanding wind simply cannot be properly accounted for by assuming some additional *external* absorption like that from the ISM. A second key difference stems from the ionization of material in the wind vs. ISM, which has important effects on the absorption opacity.

We have developed a flexible new tool, *windtabs*[1], that incorporates both an internal transport and an atomic opacity appropriate for wind absorption, and so provides a general replacement for standard ISM-like absorption models used previously [11]. Initial application suggests that much of the spectral-type vs. hardness trend inferred in *Chandra* grating spectra of O stars can actually be attributed to the stronger wind absorption for longer-wavelength, lower energy emission (see Fig. 2).

The central goal of the research proposed here is to systematically apply this new *windtabs* tool toward disentangling absorption vs. emission effects. Specifically, we propose to apply combined APEC [12] emission and *windtabs* absorption models to the same fourteen OB star grating spectra for which Walborn et al. [8] identified the X-ray hardness vs. spectral subtype trend. By accurately accounting for wind absorption, we will determine the extent to which any residual trend might then have to be attributed to a correlation of plasma emission temperature with spectral subtype (and other stellar and wind properties). We stress that no X-ray hardness or

[1]We have made the code and extensive documentation available at the XSPEC custom model repository: heasarc.gsfc.nasa.gov/docs/xanadu/xspec/models/windprof.html.

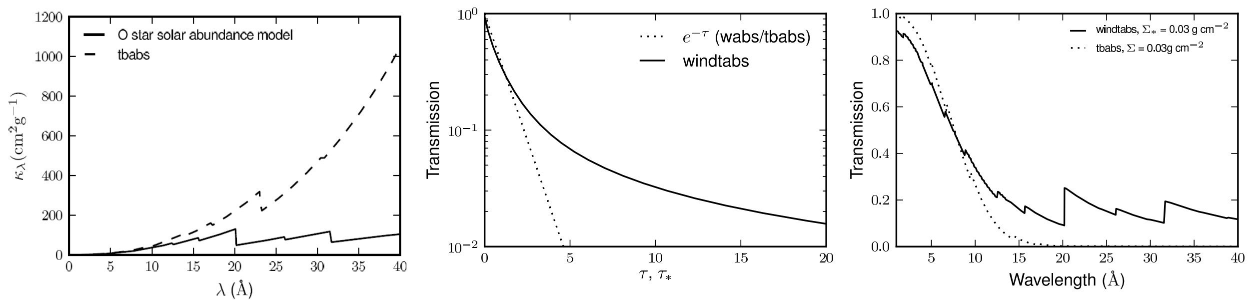

Figure 1: Three illustrations of the inapplicability of the standard ISM *tbabs* tool for modeling wind absorption. Left: the opacity in the *Chandra* bandpass of a typical O star's wind, compared to that of the neutral interstellar medium. Middle: the transmission for a source embedded in a spherically symmetric wind vs. the exponential transmission for an intervening absorber. Note how much more gradual the decline of transmission is for an optically thick embedded source compared to the exponential absorption from "slab" ISM models. Right: combining the opacity and the radiation transport model gives the wavelength-dependent transmission in the *Chandra* bandpass for a typical value of the wind column density. The excess ISM treatment is quite inaccurate.

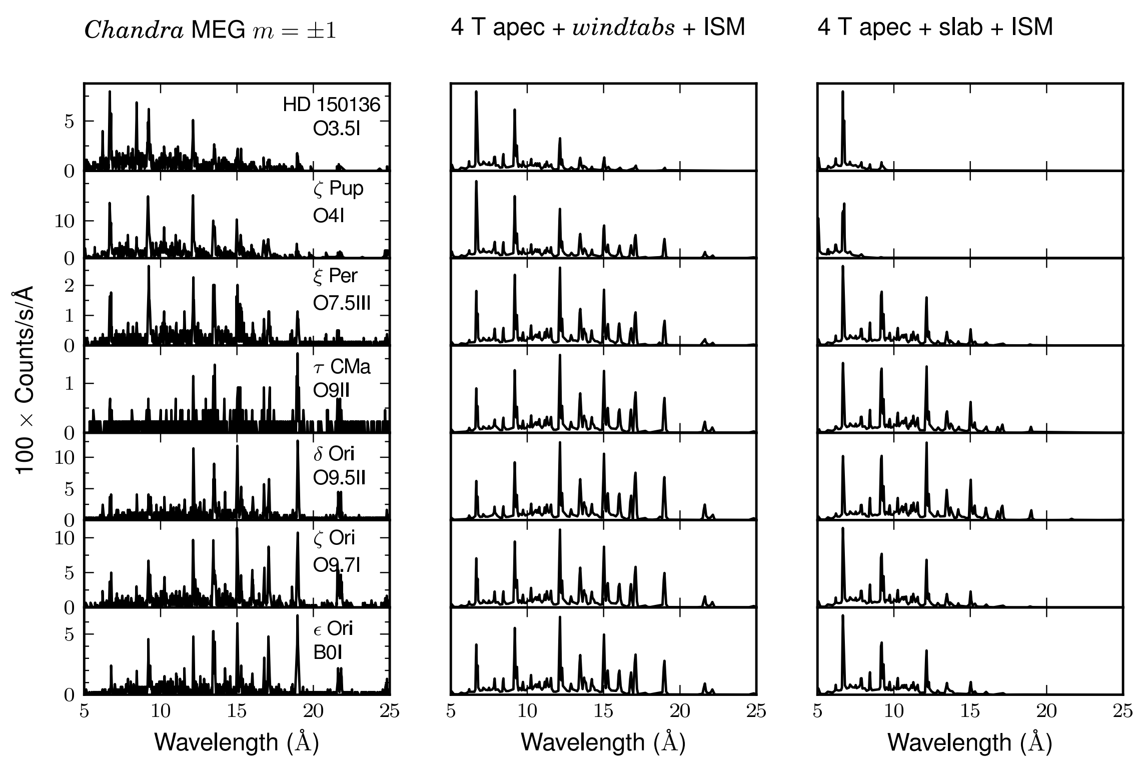

Figure 2: The seven giants and supergiants showing the X-ray hardness trend [8] (left column). A 4-temperature APEC emission model ($T_i = 0.1, 0.2, 0.4, 0.6$ keV) multiplied by the *windtabs* model, with a mass column density appropriate for each star – *not* a fit (center column). The same APEC emission model, but with the wind absorption accounted for via adding the wind and ISM column densities and using just the *tbabs* model appropriate to the ISM (right column).

plasma temperature trend with stellar spectral subtype or other property of the photospheres of OB stars is expected from EWS theory [3,13]. Even finding a small residual trend in plasma temperature would pose a strong challenge to the wind-shock model of X-ray production, and spur new theoretical developments. Moreover, the inferred level of wind absorption provides an independent measure of the wind mass-loss rate, and one that is less biased by the effects of clumping than the traditional Hα, radio free-free, and UV absorption line diagnostics [see 7,14].

These goals – determining the intrinsic X-ray emission properties and measuring mass-loss rates – directly address central aspects of the physics of OB star winds, testing fundamental theories of wind shocks and radiative driving. Thus, the proposed project would enable the most complete exploitation so far of the rich information content of the high-resolution spectra of O stars produced by *Chandra* over the last decade.

2 The *windtabs* Wind Attenuation Model

Our XSPEC model *windtabs* is a realistic model for the transmission of a distributed X-ray emitter embedded in a moderately ionized OB star wind. There are two main physical differences from neutral ISM absorption models: the ionization – which affects the atomic opacity – and the geometry. These are illustrated in Fig. 1. The first panel shows the opacity of the neutral ISM in comparison with a fiducial O star wind model. The opacity at long wavelengths is reduced because of the ionization of hydrogen and helium, and the K-shell photoelectric absorption edges are shifted because other elements are a few times ionized. The second panel shows the emission-weighted transmission of the wind as a function of fiducial optical depth, compared with the absorption from an intervening slab (as in ISM absorption models). At high optical depth, the wind model still has significant transmission, due to the geometrical distribution of the emitting plasma throughout the absorbing wind. The last panel shows the effects of the first two panels combined. The wavelength dependence of the net transmission is much less severe than for a neutral ISM slab model, which has important consequences for DEM modeling. The sole free parameter of the *windtabs* model is the characteristic wind mass column density, $\Sigma_* \equiv \kappa \dot{M}/4\pi v_\infty R_*$, from which the star's mass-loss rate can be easily computed.

3 Proof of Concept

The left-hand column of Fig. 2 shows the X-ray hardness trend in *Chandra* grating spectra of O giants and supergiants. It is this trend of hardness vs. spectral subtype that we propose to analyze by fitting multi-temperature APEC emission models in conjunction with our realistic and accurate *windtabs* absorption model. The middle column of Fig. 2 shows the same 4-temperature APEC emission model for each of the seven stars, but using a different wind mass column density, Σ_* (based on the mass-loss rate of each star). These are not fits, but just a single representative emission and absorption model without any free parameters. But the fact that they already account for much of the hardness trend illustrates the potential of formal *fitting* of the data for robustly determining the relative importance of absorption vs. intrinsic plasma emission in establishing this trend. The third column of Fig. 2 shows the same emission model but with the wind absorption treated via the standard *tbabs* absorption tool that assumes neutral ISM opacities and exponential attenuation. This demonstrates why wind attenuation has not previously been identified as a prime cause of the observed hardness trend: the exponential absorption from commonly used ISM models is too severe when the the wind is optically thick, leading, for example, to a complete suppression of long-wavelength emission in the earliest type stars, which is something not seen in the data.

We have recently employed *windtabs* in conjunction with APEC to fit the ACIS spectrum of the O supergiant HD 93129A [14]. From this model fitting, we are able to characterize the in-

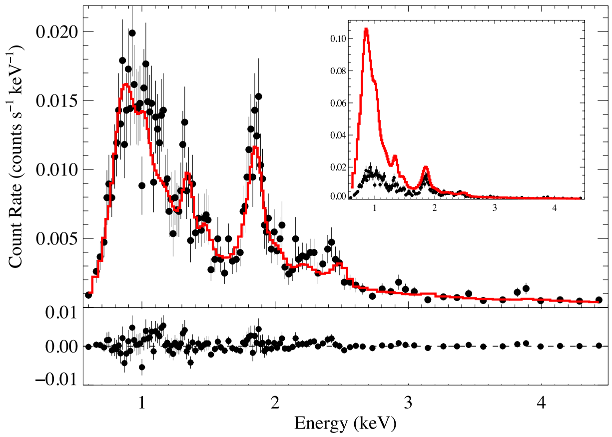

Figure 3: The ACIS CCD spectrum of the O2If* star, HD 93129A, along with the best-fit isothermal APEC model with *windtabs* (and also interstellar absorption, modeled with *tbabs*). The inset shows the same model with the wind absorption zeroed out, emphasizing both the significance of the absorption effect and its strong wavelength dependence.

trinsic emission temperature of the wind shocks, which turns out to be much lower than previous estimates, which had neglected wind absorption or modeled it crudely as excess ISM absorption. We were also able to measure the mass-loss rate of this star's wind, based on the best-fit Σ_* parameter from the *windtabs* fitting. The data and fit are shown in Fig. 3. We are proposing to extend this type of analysis to much higher resolution grating spectra of O stars, from which we will be able to extract significantly more emission temperature information than we were able to determine from the ACIS fit.

4 Proposed Analysis Program

To characterize the trend of intrinsic emission temperatures and determine the level of wind absorption, we propose here to systematically fit APEC emission models in conjunction with *windtabs* absorption models to each of the archival grating spectra of the 14 OB stars (seven main sequence stars, as well as the seven giants and supergiants shown in Fig. 2) in which the hardness trend has been identified by Walborn et al. [8].

The free parameters of this fitting process will be the temperature distribution of the APEC model(s) and the wind mass column density, $\Sigma_* = \dot{M}/4\pi R_* v_\infty$, of the *windtabs* model. We will also include ISM attenuation, but using the fixed interstellar column densities found in the literature for each star. We will use abundances specific to each star whenever possible, and also custom compute wind ionization balances (these are ingredients of the opacity model). We also will test different values of the wind parameters β and R_o, where appropriate.

While tractable, this fitting process poses several challenges, including determining the best way to identify the smallest set of required emission temperature components/parameters (4-T, say, vs. continuous DEM), finding the optimal weighting for the fit statistic (lines contain more information than the continuum), and dealing with line shapes/widths and altered f/i ratios.

Budget Narrative: PI Cohen will perform much of the data analysis, aided by co-I Leutenegger, especially with respect to the modeling the altered f/i ratios. Each will request three months of support. Cohen will also supervise two Swarthmore undergraduates who will work full time for one summer each. This project will make an ideal senior honors theses for at least one of these students. The salary support, student support, and modest travel and computer equipment will total \$75K.

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

AO1 - τ Sco (PI) - 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

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AO4 - DoAr 21 (co-I) – Jensen, Cohen, & Gagne, “No Transition Disk? Infrared Excess, H2, PAHs, and X-rays from the Weak-Lined T Tauri Star DoAr 21,” 2009, *Ap.J.*, 703, 252

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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

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, analysis, and modeling
X-ray/EUV astronomy spectral analysis, time-variability analysis, hot stars, young stars
Laboratory astrophysics modeling, spectroscopy, and experiment design of x-ray photoionized plasmas; plasmas heated by magnetic reconnection
Inertial confinement fusion experiment design and modeling

SELECTED PUBLICATIONS

Leutenegger, Cohen, Zsargo, Martell ('09), MacArthur ('11), Owocki,, Gagne, & Hillier, "Modeling Broadband X-ray Absorption of Massive Star Winds," 2010, *Ap.J.*, 719, 1767

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