

## Wind Opacity Issues

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OFH2006 shows this plot of wind opacity for four stars (below), from “detailed” wind modeling using PoWR. It appears that the only K-shell edge is that of (a single ion state of) nitrogen. This seems pretty crude. And it makes me wonder what elements are included in the calculation of the overall opacity and how reliable the smooth portions of the curves are.

As you look at the figures in this document, keep in mind that some plot cross section and some plot the radius of optical depth unity,  $R_1$ .  $R_1$  is very similar to  $\tau_{\text{star}}$  for large  $\tau_{\text{star}}$  values, and they both depend on mass-loss rate, stellar radius, and wind velocity, in addition to the atomic opacity. This is important for comparisons between stars and even between different work, which makes different assumptions about these stellar parameters. Also keep in mind that some of these plots have linear y-axes while others have logarithmic y-axes which are, in some cases, quite compressed.

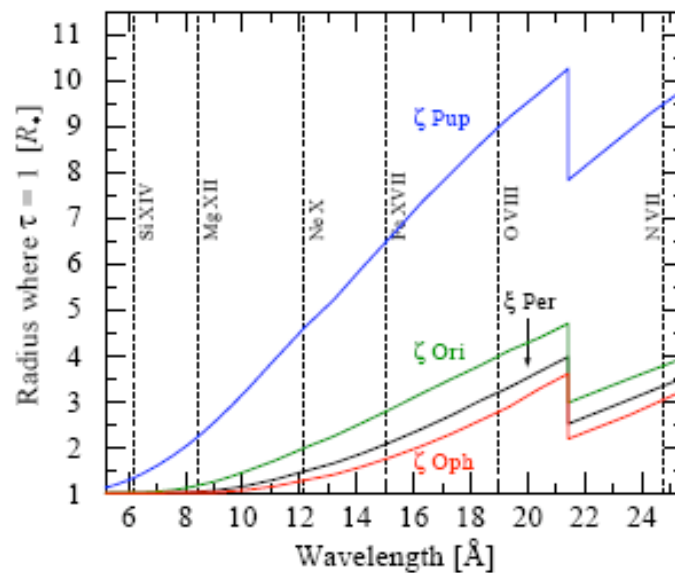


Figure 5. The radius where the radial optical depth of the wind becomes unity in dependence on the wavelength in the Chandra HETGS/MEG range. The calculations were done using the PoWR stellar atmosphere code (see text) with stellar parameters from Table 2. The prominent edge at  $\lambda 21.5 \text{ \AA}$  is due to oxygen. The vertical dashed lines correspond to the wavelengths of the studied lines (as indicated).

Below are several other calculations of wind opacity in the soft x-ray for OB stars from the literature. OFH06 would like to argue that the wavelength-dependence of the opacity is steep across the MEG range (functionally, for our purposes,  $\sim 8$  to 22 Angstroms, or 0.6 to 1.3 keV –  $E$  (keV) =  $12.4/\lambda$  (Å)), but see the calculations below and the effects of multiple ion stages and elements.

This calculation (from Waldron et al. 1998) is for a “typical early O star” and is pretty detailed. It shows the multiple ion stages, K- and L-shells of several elements, and the deviations from neutral (ISM) opacity, with the associated shifting of the K-shell edges to higher energies.

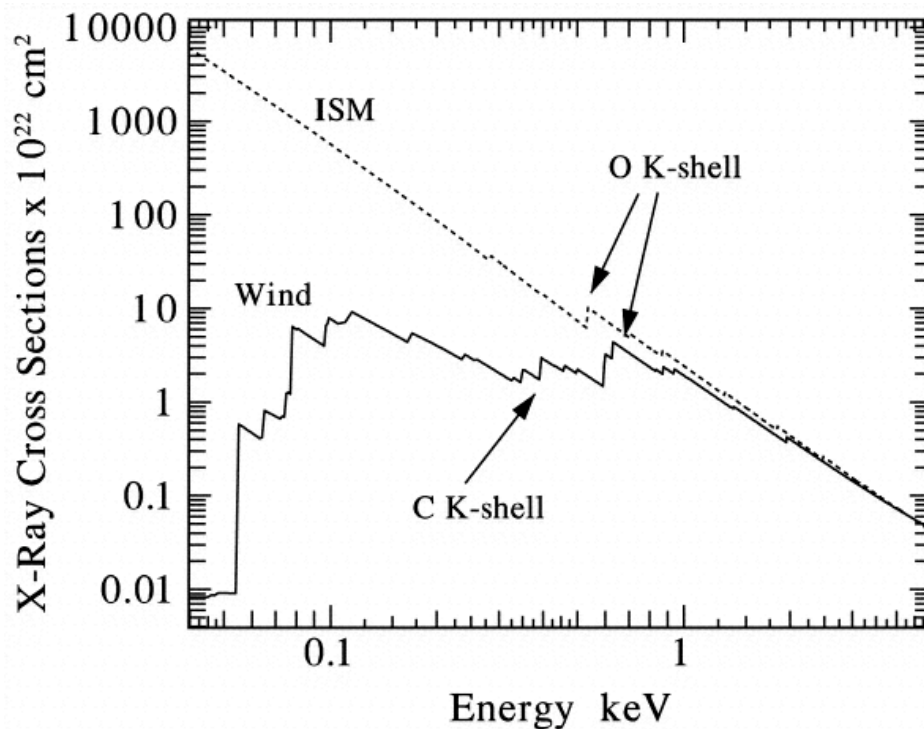


FIG. 2.—Comparison of ISM (cold) and stellar wind (warm) X-ray cross sections for a typical early O star ( $T_{\text{eff}} = 40,000$  K). Note the large number of wind absorption edges and the relative flatness of the wind cross sections between 0.1 and 1 keV. Above 0.6 keV, the ISM and wind cross sections are essentially the same. The C and O K-shell edges are indicated. Comparing the ISM and wind cross sections we notice an energy shift ( $\sim 0.08$  keV) of the O K-shell edge, which is a reflection of the higher ionization state of the wind. [from Waldron et al., 1998, ApJS, 118, 217]

Similar (but somewhat different) overall opacity for a cooler early B star (specifically, epsilon CMa – the solid line; the dashed line is the ISM). Note more He+ than in Waldron's calculation because the star is cooler and the wind is less ionized. Also, the atomic abundances are probably different (I used canonical B star – non-solar – abundances for this calculation).

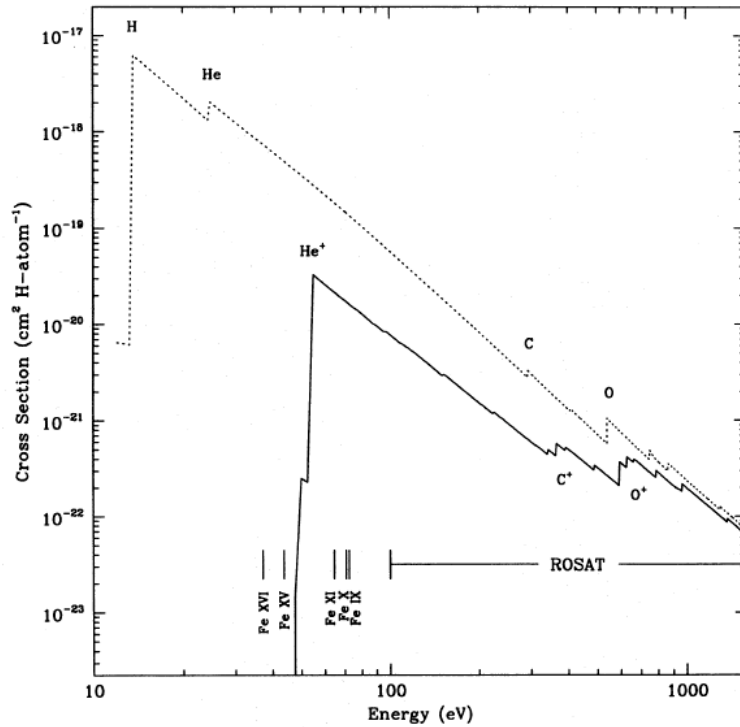
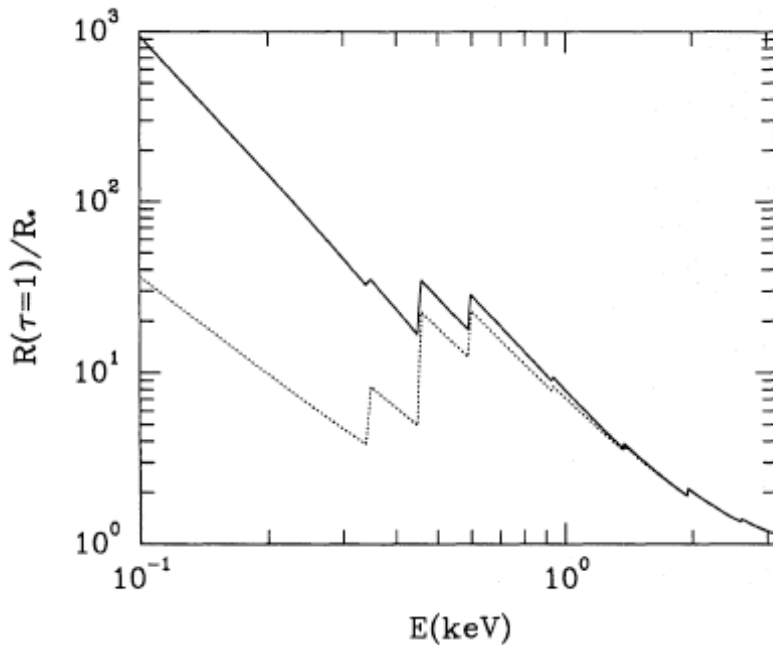


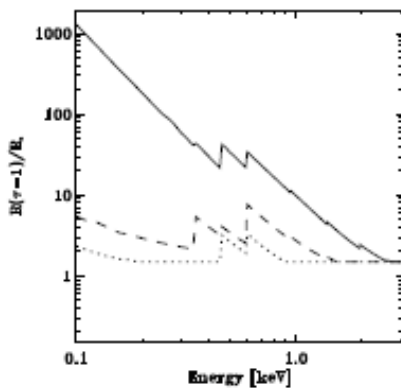
FIG. 4.—The cross section per hydrogen atom for the ions in the stellar wind (*solid line*) and for neutral elements in the interstellar medium (*dotted line*) is plotted vs. photon energy. It should be noted that while the interstellar medium has a much higher opacity per particle than does the wind material, the total column of material in the interstellar medium is, for  $\epsilon$  CMa, much less than the wind column. Therefore above 54 eV the stellar wind is the primary source of opacity. The locations of the five detected EUV lines are indicated along the bottom of the plot, along with the *ROSAT* bandpass.

This is from the Hillier et al. (1993) analysis and modeling of zeta Pup (note: same y-axis as OFH06). Multiple elements (and according to the caption, accounting for the specific abundances of zeta Pup) are present, but maybe not multiple ionization states.



**Fig. 1.** Radius of optical depth unity as a function of X-ray energy. (solid - Model 1; dashed - Model 2). The observed X-ray flux scales approximately as the inverse of  $R(\tau = 1)$ . Note the strong K shell edge (near 0.5 keV) due to nitrogen, whose abundance is considerably enhanced over solar values (see Table 2)

And this is from Feldmeier et al., A&A, 320, 899 (1997). The zeta Pup curve looks identical to the one in the above figure, from Hillier et al.



**Fig. 9.** Location of optical depth unity for X-rays in the ROSAT energy band for the three stars from Table 1:  $\zeta$  Pup (full);  $\zeta$  Ori (dotted);  $\zeta$  Ori (dashed).

In summary:

There's a fair amount of disagreement in (a) the overall level of opacity (e.g. note how much larger  $R_1$  is in zeta Pup according to Hillier et al. than OFH's calculations indicate – we can look into how the choices of stellar and wind parameters differ in these two papers); and (b) the wavelength-dependence of the opacity, especially in the spectral region of interest for Chandra grating observations (roughly 0.5 to 1+ keV).

The transition from one CNO element to the next in this spectral region, and the combined effects of ionization edges and continuum opacities for the different ionization stages present in the winds, conspire to significantly flatten the opacity in the spectral region of interest – if they're taken into account! However, how the opacity is affected in detail will depend on various model assumptions (including abundances – which will also affect the overall opacity).

Detailed calculations that focus on the ionization state distribution and abundances are necessary in order to interpret the spectral data and to assess the implications of the apparent grayness of the observed line profiles.

There also seems to be some disagreement about the overall opacity level (e.g. the shapes of some of these opacity curves agree between some of the studies even while the absolute numbers do not). While doing our own modeling, it would be worthwhile to determine what the sources of the disagreements in these previous studies are.