Clumping in Hot Star Winds
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X-ray line emission produced in clump bow shocks

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We summarize Chandra observations of the emission line profiles from 17 OB stars. The lines tend to be broad and unshifted. The forbidden/intercombination line ratios arising from Helium-like ions provide radial distance information for the X-ray emission sources, while the H-like to He-like line ratios provide X-ray temperatures, and thus also source temperature versus radius distributions. OB stars usually show power law differential emission measure distributions versus temperature. In models of bow shocks, we find a power law differential emission measure, a wide range of ion stages, and the bow shock flow around the clumps provides transverse velocities comparable to HWHM values. We find that the bow shock results for the line profile properties, consistent with the observations of X-ray line emission for a broad range of OB star properties.

1 Chandra observations of OB line emission

Chandra Observations provided many surprises relative to pre-launch expectations, of MacFarlane et al. (1991). We expected X-rays to be forming in driven-wave shocks, where the incident speed relative to the shock front provides the temperature of the shocked gas. The high density at the contact surface is determined by the the square of the incident flow Mach number × the density of the incident material, $\rho_{\rm wind}$. This picture led to predictions that line profiles should be very broad, and depending on the overlying cool wind column density, either nearly flat topped, or skewed significantly, such that the "blue (shortward) side", arising from the near side of the star, is at a significantly higher flux than the "red side" arising from the far side of the star. Thus, the lines were predicted to be broad, skewed, and with a peak flux shifted toward the blue side.

Observations of lines from 17 OB stars have been presented by Waldron and Cassinelli (2007). The properties of three luminosity classes are considered (Supergiants, Giants, and MS stars). As expected, almost all lines are found to be broad with a typical $HWHM = 0.4 \times v_\infty$. However, the lines are symmetric, showing negligible shift of line centroid, and are well represented by Gaussian line profiles. Figure 1 shows the derived radial dependence of the normalized HWHM and peak line shift, V_P. The radial dependence, expressed in terms of the ambient velocity, is determined from the fir-inferred radii (R_{fir}) obtained from the He-like f/i line ratios, as discussed by Waldron and Cassinelli (2007).

CHandra high energy resolution data provides a means to derive information about the radial distances to the X-ray sources (here, clump shocks) by using the forbidden, intercombination, resonance (fir) lines from Helium-like ions. In order of increasing ionization stage along with their associated r-line wavelength, the strongest He-like fir ions that have been observed by Chandra are: O vii (21.60 Å), Ne ix (13.45 Å), Mg xi (9.17 Å), Si xiii (6.65 Å), and S xv (5.04 Å).

A surprising result found even in the earliest Chandra observations of Waldron and Cassinelli (2001) is that the lower energy He-like ion stages (longer wavelengths) originate farther out in the wind as compared to the higher energy He-like ion stages. We explained this by the fact that "cool" wind continuum opacity to X-rays increases roughly as λ^3, and that the R_{fir} corresponds rather well to the radii of X-ray optical depth unity in the wind. This nice correlation still holds in our survey, especially for the supergiants, *but* only if one assumes the standard mass loss rates for these stars instead of the reduced mass loss rates that we have been discussing here (e.g., Fullerton et al. 2006). Although the giants and MS stars with lower mass loss rates (smaller optical depths) show more dispersal in the relationship, there is no evidence of any X-ray emission arising from below the associated optical depth unit radii. Furthermore, regardless of luminosity class, *none of the stars show high energy ion stages forming far from the star.* Thus, another major problem revealed by X-ray lines is that the high ion stages such as S xv form *too near* the star, i.e., where $U_{\rm shock\,jump} > v_{\rm wind}$.

In Figure 2, temperatures from the line ratios of H-like to He-like ions are plotted versus, R_{fir}. For the supergiants, one does not see ions arising from below a depth that corresponds well continuum optical depth unity.

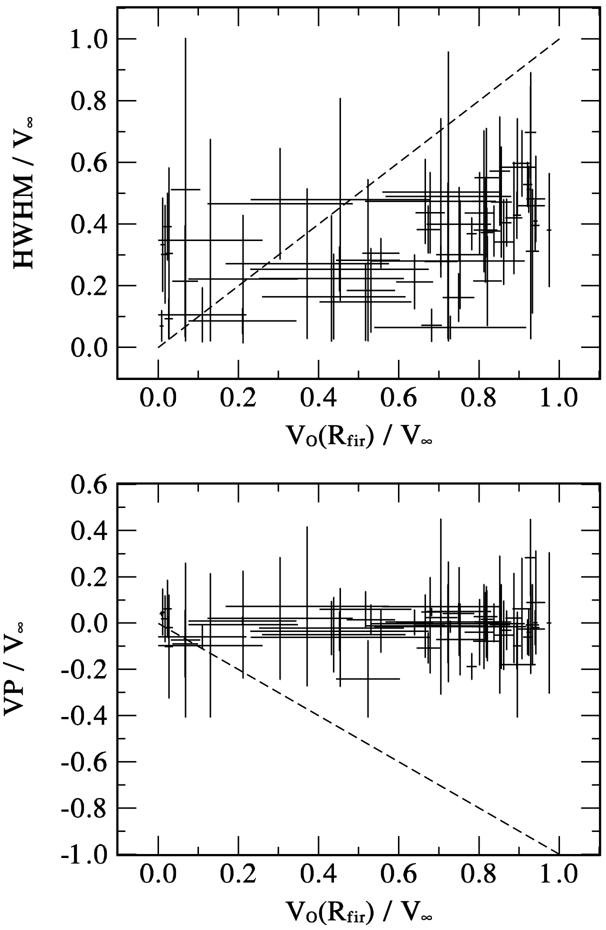

Figure 1: The upper panel shows CHANDRA X-ray line widths, (HWHM) vs. wind speed at line formation radius (R_{fir}), for lines in 17 OB stars. The widths show a distribution for 0. to 0.6 V_∞, with no clear indication of a radial dependence. In the Lower panel are the centroid line shifts vs. wind speed; note that the lines are always nearly unshifted and do not have the expected blueshift

For the lower luminosity classes in Figure 2, one sees ions originating at a broader range of radii, but even for these stars, high ions are found not to arise at large radial distances.

Another important property of OB-star X-rays has been found by Wojdowski and Schultz (2005), who derive the stellar Differential Emission Measure (DEM) (= $dEM/d\log T$ vs. log T). For most OB stars, the DEM is a simple downward sloping power-law, from $T = 10^6$ up to a $T_{\max} > 10^7$ K. (Highly magnetic stars can have DEM increasing with T.)

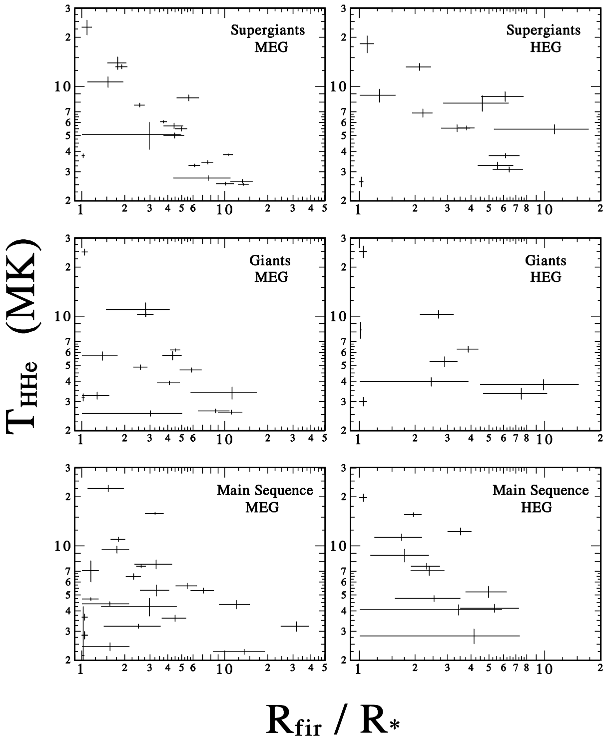

Figure 2: The X-ray source temperature versus radius distributions for three OB luminosity classes, using both the CHANDRA Medium Energy Grating and High Energy Grating. The temperatures from the H-like to He-like line ratios are plotted versus the R_{fir} line formation radii.

2 Bow shock modeling

We have used the hydrodynamical code (ENO) of Cho and Lazarian (2001) to derive the temperature, velocity, density structure of post shock region for a wind colliding with an impenetrable sphere. We find a power law differential emission measure, in Figure 3, which is similar to that found observationally by Wojdowski and Schulz (2005). Thus, there is a wide range of ionization at each clump, with the maximum temperature set by $T_{\max} = 14$ MK $(v_{1000})^2$. The emission measure for the lower temperatures (and hence the lower ion stages), arises from the fact that a bow shock has an increased area toward the wings where the shock is increasingly oblique. Across an oblique shock there is a reduced change in flow speed and hence a reduced temperature increase is expected. The hydrodynamical models also show a significant flow of X-ray emitting gas around the clump face with a sideways speed of about 45% the incident wind speed.

We find, in contrast with Planar shocks (e.g., Feldmeier 1995), that the density behind the shock does not rise above 4× the wind density and so the X-ray emission is from near the shock front. Hence, we say that we can use the "On the Shock" or *OTSh* approximation for a simple analyses of bow shocks.

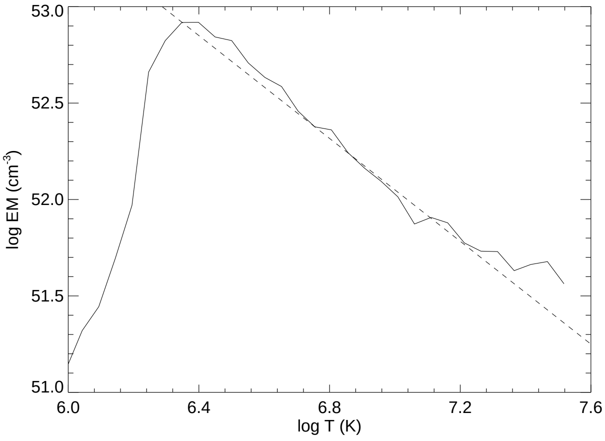

Figure 3: The Emission Measure versus Temperature power law distribution, with the maximum T set by the speed of the incident wind relative to the shock, $U_\circ$.

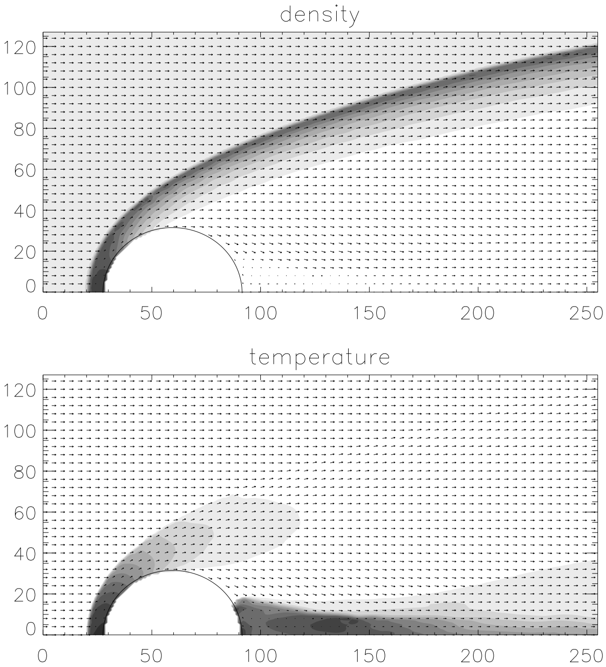

Figure 4: Bow shock structure. The X-ray production mostly occurs very near the shock at uniform density near $4\rho_{\rm wind}$.

As for the observed near-zero velocity shift and broad HWHM of the lines, these can best be explained if we have the X-ray line emission arising from the sides of the star as seen by the observer (i.e., perpendicular to the line-of-sight). This region contains a spread in speeds around the, $v_z = 0$, iso-velocity surface. A concentration of emission from that sector of the wind would occur if the cool clump absorbs the line emission from the bow shock at its star-ward face. Thus we see an enhanced contribution from the regions at, and symmetric about, $v_z = 0$. This counters the expected tendency to see the blueward-shifted and -skewed line emission.

There is also the problem regarding the very high temperatures and correspondingly high high ions that are inferred to be present at small radii, the "near-star high-ion problem", as we call it. This could perhaps be explained by the infalling clump idea proposed by Howk et al. (2000). They point out that this could work for stars with lower wind momentum fluxes that produce a smaller drag force. As for the other stars, there are other possibilities for producing high relative speeds between the wind and the clumps.

In summary, accounting for bow shocks around clumps in winds can potentially explain: a) the zero centroid shift problem, ($V_p \approx 0.0$), (if the radiation is primarily from clumps to the side of the star). b) the broad line widths, because the bow shock sideways velocity plus a range in v_z is comparable to the HWHM) c)the DEM power laws, which follows directly from the wind -oblique shock interaction. d) the large range in ions and ion temperatures, also arising from the oblique shocks, and perhaps e) the concentration of the highest ions and highest temperatures relatively near the star, if clumps can have large speeds relative to the wind near the star.

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Najarro: What if clumping disappears towards the outer regions of the winds. Would that not be consistent with a need for a reduction of the mass loss rate in regards to the UV lines of P V and with X-rays from the outside?

Cassinelli: Certainly one of the possible solutions to the P V problem, that seems to require a large reduction in mass loss rate, is to have Phosphorus Auger-ionized to even higher stages of ionization by the X-rays passing through the winds. An advantange of clumps is that the X-rays would be produced in close proximity to the clumps. In the $\dot{M}$ reduction papers, it is assumed that P V is the dominant stage of ionization even in the dense clumps, and so the P V line absorption is independent of clumping. However with a strong source of nearby X-ray emission the dominant stage of ionization could be P VII or P VIII. As for the location of the clumps and their associated X-rays: it certainly seems plausible that the clumpiness could decrease with radius, or that the velocity of the clumps relative to the ambient wind could decrease with radius, which would result in the production of softer X-rays. If the mass loss rate is actually the high, traditional value, one needs to find a way to change the ionization stage of P V. If the mass loss rate is actually very low, as has been proposed, one would not need to have the X-rays do anything to the ionization of P V. However, my feeling is that if we know that there is clumping it is inevitable that X-rays are produced. If the X-rays were to be absent in the outer regions then one would get less of a P change at high Doppler shift, and I do not think that is what is observed. The radio flux tends to form in the outer regions, and clumpiness seems to be needed to enhance that flux. The UV line profiles are broad and these indicate that the line is formed over a wide range in velocity and hence in radius. The fraction of the wind that is hot enough to produce X-rays is really quite small, like 10^{-3}, typically, and the R_{fir} diagnostic shows that the X-rays are formed over a range in radii from near the star out to say $10\,R_*$. So I do not see that eliminating the clumping in the outer regions helps much.

Cohen: Why do you assume that the jump velocity at a shock is half the wind speed?

Cassinelli: It is based on the shock models of Glenn Cooper that he did in his thesis at U. Delaware and work in Madison. Also the shock models of Achim Feldmeier et al. (1997) typically showed jumps of about half the speed of the incident gas. Subsequent infall of a clump would allow for a shock jump to be larger than the local wind speed, producing the high temperatures that seem to be needed.

Puls: Which temperature and which emission radius are you proposing from your X-ray studies.

Cassinelli: The highest ion stages in the Waldron and Cassinelli (2007) study are of S XV and S XVI and of Si XIII and Si XIV and these two pairs of ions form in temperatures in the range 13 to 25 million K and 10 to 16 million K, respectively. The fir radii are in the range 1.1 to 2.5 R_*. So we see the "near star high ion problem" as an important new property of hot-star winds.

Feldmeier: You suggest that clumps fall back to the star. Stan and I recently did some simulations where we increased and decreased the base density by up to a factor of 300. The effect of the density decrease was the creation of a velocity plateau, as I showed in my talk yesterday. But there is essentially no effect of a density increase. So I am a bit uncertain about how one can actually create a backfalling clump.

Cassinelli: In the Howk et al. paper (2000, ApJ, 534, 348), we assumed that the density in the clump is increased relative to the ambient wind by a factor (Mach number)^2. This is an even larger factor than you assumed. The high density (and a specific mass range, near 10^{19} gram) means that the cross sectional area is rather small and this area determines the continuum radiation driving, i.e. there is no velocity gradient in the clump. The dominant outward acceleration on the clump is the wind drag force acting on the area πR^2 of the clump, and since the clump is assumed to form where its velocity is less than the escape speed, it could fall back, and hence lead to the large shock speed needed for the hard X-ray emission (of τ Sco). The enhancement of ρ in your velocity plateau is smaller than what we are envisioning.