X-rays from magnetically confined wind shocks: effect of cooling-regulated shock retreat

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Abstract

We use 2D MHD simulations to examine the effects of radiative cooling and inverse Compton (IC) cooling on X-ray emission from magnetically confined wind shocks (MCWS) in magnetic massive stars with radiatively driven stellar winds. For the standard dependence of mass loss rate on luminosity, Mdot ~ $L^{1.7}$, the scaling of IC cooling with *L* and radiative cooling with Mdot means that IC cooling become formally more important for lower luminosity stars. However, the overall effect of including IC cooling is quite modest. But for stars with high enough mass loss to keep the shocks radiative, the MHD simulations indicate a linear scaling of X-ray luminosity with mass loss rate; but for lower luminosity stars with weak winds, X-ray emission is reduced and softened by a ***shock retreat*** resulting from the larger post-shock cooling length, which within the fixed length of a closed magnetic loop forces the shock back to lower pre-shock wind speeds. A semi-analytic scaling yields X-ray luminosities that are in close agreement to time-averages computed from the MHD simulations. The results here provide a good basis for interpreting available X-ray observations from the growing list of massive stars with confirmed large-scale magnetic fields.

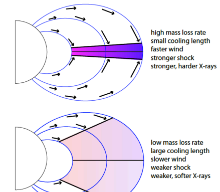
Massive-Star Winds

- Over the course of their lifetimes, hot, luminous, massive (OB-type) stars lose large amount of mass in nearly continuous outflow called a stellar wind.
- These winds are driven by scattering of the star's continuum radiaton in a large ensemble of spectral lines (Castor, Abbott & Klein 1975; CAK)
- There is extensive evidence for variability and structure on both small and large scales.
- Our simulations show that magnetic fields may explain some of the large scale variability in wind flow, Hα, UV and X-ray emissions from hot stars.
- There have been a number of positive detection of magnetic fields in hot stars recently by Magnetism in Massive Stars (**MiMeS**) Project.

Cooling: radiative, adiabatic and Inverse Compton

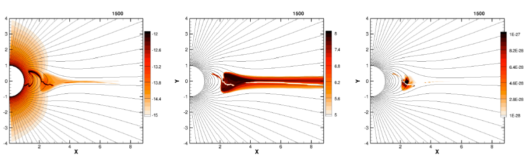
- UV photoionization heating keeps the wind at floor T, comparable to Teff
- In shocks, such heating is unimportant; cooling becomes dominant
- Three types of cooling are important:
  - radiative
  - adiabatic expansion
  - Inverse Compton (IC)
- Radiative cooling is dominant for high mass loss stars, whereas IC formally dominates at low luminosities, but as we will see IC has relatively minor effect.
- We vary cooling efficiency as a proxy for variations in Mdot and L

Magnetically Confined Wind-Shocks (MCWS)



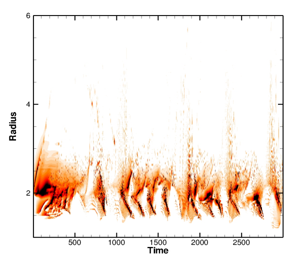
The 'shock retreat' from inefficient cooling. Wind outflow from opposite hemispheres is channelled into a collision near the loop top. For the high Mdot case (upper panel), the efficient cooling keeps the shock-heated gas within a narrow cooling layer, allowing the pre-shock wind to accelerate to a high speed and so produce strong shocks with hard X-ray emission. For the low Mdot case (lower panel), the inefficient cooling forces a shock retreat down to lower radii with slower pre-shock wind, leading to weaker shocks with softer X-ray emission.

MCWS X-rays from standard model

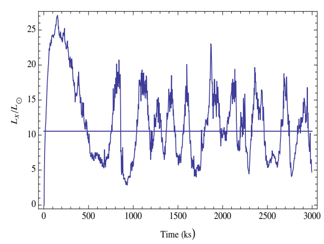


Color plots of log density (left) and log temperature (middle) for arbitrary snapshot of structure in the standard model with η_*= 100 and no IC cooling. The right panel plots the proxy X-ray emission weighted by the radius r on a linear scale for a threshold X-ray temperature Tx = 1.5 MK, suggesting the location for most x-rays.

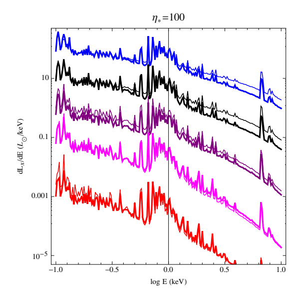
Results



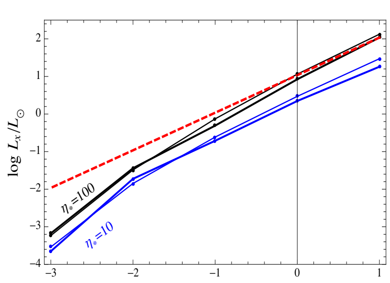
Radial distribution of latitudinally integrated X-ray emission above an X-ray threshold, plotted vs. radius (in Rstar) and time (in ks) for the standard model.



For standard model simulations with η_*=100, the time variation of cumulative X-ray luminosity Lx ($E>E_x$,t) above X-ray threshold energy E_x = 0.3keV, plotted in units of Lsun. The horizontal line shows the time-averaged value L_x ~ 67 Lsun, computed over times t>500 ks, after the model has relaxed from its initial condition.

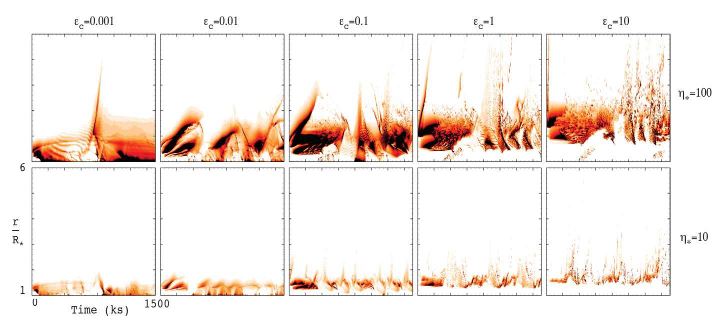


Log of time-averaged X-ray luminosity, log L_X, for X-rays above E_X = 0.3 keV, plotted vs. log of cooling efficiency log ε_c , which acts as a proxy for mass loss rate Mdot. The thick and normal thickness lines represent models with and without IC cooling.



Log ε_c ~ Log $\dot{M}$

Log of time-averaged X-ray luminosity, log L_X, for X-rays above E_X = 0.3 keV, plotted vs. log of cooling log ε_c , which acts as a proxy for mass loss rate Mdot. The upper (black) and lower (blue) curves are respectively for η_*=100 and η_*=10, and the thick and normal thickness lines represent models with and without IC cooling. The dashed red line shows a linear relation normalized to values for the η_*=100 model with the strongest cooling ε_c = 10.



Mosaic of the radius and time variation of latitudinal- and energy-integrated X-ray emission above a threshold E_X =0.3 keV for models with IC cooling and η_*=100 (upper row) or η_*=10 (lower row), with columns representing the 5 values of cooling efficiency ε_c, ranging from 10^{-3} (left) to 10^1 (right). Between the η_*=10 vs. 100 models, the relative color strength reflects the relative X-ray luminosity. Within each η_* row, the emission is scaled by the total L_X for each ε_c, and plotted on a common, linear color scale. For decreasing $\varepsilon_c$the decrease in the lower boundary radius for X-ray emission reflects the stronger shock retreat, while the higher upper radial extent of X-rays in the η_*=100 vs. 10 models reflects the larger Alfvén radius R_A.

Conclusions

- Inverse Compton cooling has a quite modest overall effect on the broad scaling of X-ray emission.
- The reduced efficiency of radiative cooling from a lower mass loss rate causes a shock retreat to lower speed wind, leading to weaker shocks. This lowers and softens the X-ray emission, making the Mdot dependence of L_X steeper than the linear scaling seen at higher Mdot without shock retreat.
- The overall scalings of time-averaged X-rays in the numerical MHD simulations are well matched by the L_X computed from a semi-analytic "XADM". However, the values of L_X are about a factor 5 lower in the MHD models, mostly likely reflecting an overall inefficiency of X-ray emission from the repeated episodes of dynamical infall.

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