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

A. ud-Doula¹, S. Owocki², R. Townsend³, V. Petit², D. Cohen⁴

¹Penn State Worthington Scranton, USA; ²Bartol Research Institute, University of Delaware, USA; ³Department of Astronomy, University of Wisconsin-Madison, USA; ⁴Department of Physics and Astronomy, Swarthmore College, USA.

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 massive magnetic stars with radiatively driven stellar winds. For the standard dependence of mass loss rate on luminosity, Mdot \sim L^{-1}, the scaling of IC cooling with L and radiative cooling with Mdot means that IC cooling becomes 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 shocks, X-ray emission is reduced and softened by a shock revent resulting from the larger post-shock cooling length, which within the fixed length of a closed magnetic cooling is quite modest. But for stars with high enough mass loss luminosity stars. However, the overall effect of including IC cooling means that IC cooling become formally more important for lower cooling-regulated shock retreat. The 'shock retreat' from inefficient cooling. Wind outflow from white dwarfs is channelled into a collimation 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.

Color plots of log density (left) and log temperature (middle) for arbitrary snapshot of structure in the standard model with \eta_c = 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.

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 \eta_c=100, the time variation of cumulative X-ray luminosity L_{X} (\tilde{E}_{X}>\tilde{E}_{X,T}) above X-ray threshold energy \tilde{E}_{X}=3.0 keV, plotted in units of Lsun. The horizontal line shows the time-averaged value L_{X}\sim 67 L_{sun}, 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 \tilde{E}_{X}=0.3 keV, plotted vs. log of cooling efficiency log \epsilon_c, which acts as a proxy for mass loss rate Mdot. 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 \eta_c=100 model with the strongest cooling \epsilon_c = 10.

Mosaic of the radius and time variation of latitudinal- and energy-integrated X-ray emission above a threshold \tilde{E}_{X}=0.3 keV for models with IC cooling and \eta_c=100 (upper row) or \eta_c=10 (lower row), with columns representing the 5 values of cooling efficiency \epsilon_c ranging from 10^{-3} (left) to 10^{3} (right). Between the \eta_c=10 vs. 100 models, the relative color strength reflects the relative X-ray luminosity. Within each \eta_c row, the emission is scaled by the total L_{X} for each \epsilon_c and plotted on a common, linear color scale. For decreasing \epsilon_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 \eta_c=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.

Support for this work was provided by NASA through Chandra Fellow awards TFH-10335A, TFH-10326 and TFH-10328 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. The X-ray data were carried out with partial support by NASA/GSFC and NASA/CGS/MSL.