Active OB stars: structure, evolution, mass loss, and critical limits
Proceedings IAU Symposium No. 272, 2010
C. Neiner, G. Wade, G. Meynet & G. Peters, eds.

doi:10.1017/S1743921311011562

X-ray emission from hydrodynamical wind simulations in non-LTE models

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Abstract. Massive hot stars are strong sources of X-ray emission originating in their winds. Although hydrodynamical wind simulations that are able to predict this X-ray emission are available, the inclusion of X-rays in stationary wind models is usually based on crude approximations. To improve this, we use results from time-dependent hydrodynamical simulations of the line-driven wind instability to derive an analytical approximation of X-ray emission in the stellar wind. We use this approximation in our non-LTE wind models and find that an improved inclusion of X-rays leads to a better agreement between model ionization fractions and those derived from observations. Furthermore, the slope of the Lx-L relation is in better agreement with observations, albeit the X-ray luminosity is underestimated by a factor of three. We propose that a possible solution for this discrepancy is connected with the wind porosity.

Keywords. stars: winds, outflows, stars: early-type, hydrodynamics, X-rays: stars

1. X-rays in non-LTE wind models

Hot stars are known as X-ray sources. These X-rays originate in the stellar wind. As they influence the wind ionization, they should be included in the non-LTE wind models.

There have been earlier attempts to include X-ray emission in non-LTE wind models. They were either based on simplified analytical models, or the X-ray emission was included using free parameters (aka the "filling factor") describing the hot wind part. Here we use the results of hydrodynamical simulations of Feldmeier *et al.* (1997) to describe the X-ray emission in a compact form and include it in our non-LTE wind models.

2. Models: hydrodynamical simulations and non-LTE models

The X-ray emissivity in our models is derived employing hydrodynamical simulation of Feldmeier *et al.* (1997) calculated for ζ Ori A. A turbulent velocity variation at the wind bases was introduced as seed perturbation.

To incorporate the results of hydrodynamical simulations in non-LTE wind code in a manageable way, we approximate the emission from hydrodynamical simulations as a polynomial function. This could be done in two ways. The first way is to approximate the resulting X-ray emission, the second one is to find a polynomial that fits the temperature structure of the simulation (see Krtička *et al.* (2009) for the corresponding fits).

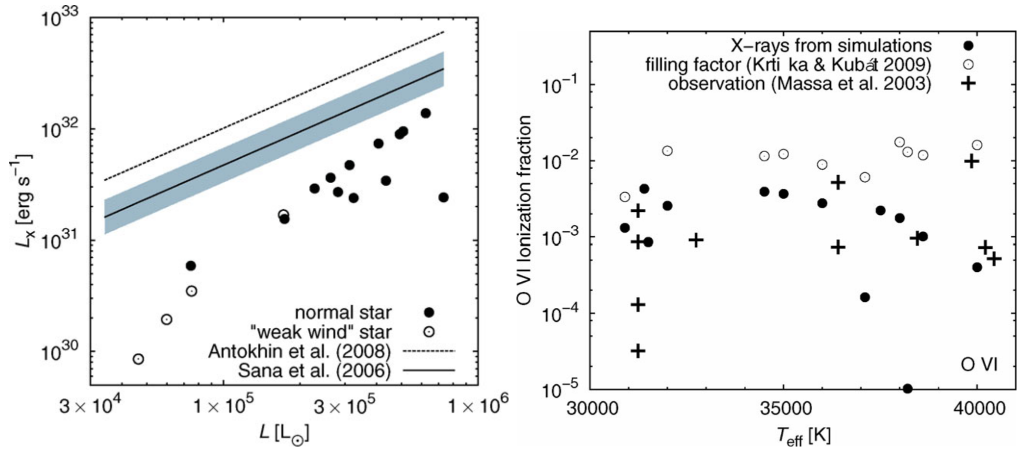

Figure 1. Left: The dependence of the total X-ray luminosity on the bolometric luminosity calculated using non-LTE models with X-ray emissivity from hydrodynamical simulations (filled and empty circles) for individual stars compared with the mean observational relations. Right: Comparison of predicted and observational ionization fraction as a function of the effective temperature. Filled circles refer to the models with X-ray emission from hydrodynamical simulations, and open circles refer to the models with X-ray emission described using filling factor.

Compared to other approximations, the temperature of X-ray emitting gas decreases with radius in the outer wind, and is described by a distribution function, which is more realistic than assuming just one temperature.

We include X-ray emission from hydrodynamical simulations into our stationary, spherically symmetric non-LTE wind model (Krtička & Kubát 2009).

3. Application: $L_{\rm X} - L$ relationship and ionization fractions

The predicted X-ray luminosities for stars with optically thick winds ($L \gtrsim 10^5\,{\rm L}_\odot$) are on average lower roughly by a factor of three than the observed ones (Fig. 1, left panel). This may originate in our neglect of macroclumping, which causes a lower X-ray opacity (Oskinova *et al.* 2004). On the other hand, the derived slope of the $L_{\rm X} - L$ relation for stars with optically thick winds, $L_{\rm X} \sim L^{1.0}$, is in a good agreement with observations.

The X-rays also influence the ionization fractions (Fig. 1, right panel). Although the non-LTE models calculated with X-ray emission from hydrodynamical wind simulations give a too low emergent X-ray luminosity, the ionization structure of these models corresponds in general much better to the trends derived from observations.

Acknowledgements

This research was supported by grant GA ČR 205/08/0003.

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