Modelling bow shocks of massive runaway stars

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Summary

We study the circumstellar medium of massive stars, and aim particularly at investigating the role and the effects of stellar motion with respect to the interstellar medium (ISM). The resulting nebulae are bow-shocks with observable characteristics that are determined by stellar properties such as the mass-loss rate, the wind density and the wind velocity, but also by ISM parameters such as its density or the strength of its background magnetic field. To this end, massive stars (stars with masses above 10 Mo) are considered which move through the ISM and evolve at the same time. They are modelled with various different physical processes such as radiative cooling and heat conduction using the PLUTO code.

Introduction

Models of the circumstellar medium of massive stars can constrain stellar evolution models, since the properties of circumstellar nebulae are like fingerprints of the previous evolutionary history of their central stars. Additionally, such models provide the amounts of energy, momentum and of chemical elements which massive stars return into the ISM, which affect the evolution of star forming galaxies. This PhD project aims at producing a grid of simulations modelling the stellar wind-ISM interaction for a moving source through the ISM, during its complete life cycle, from the main sequence to the late evolutionary phases, including supernova stage. Here, we present test models for main sequence O stars, and modifications to the PLUTO MHD code (Mignone et al., 2006) to model bow shocks. We investigate the role of thermal conduction in realistic bow shocks. The effects of stellar velocity on the shape and the structure of bow shocks are presented for the same main sequence O star.

Example of bow shock. Credit:NASA/JPL-Caltech/WISE Team.

Effects of stellar velocity

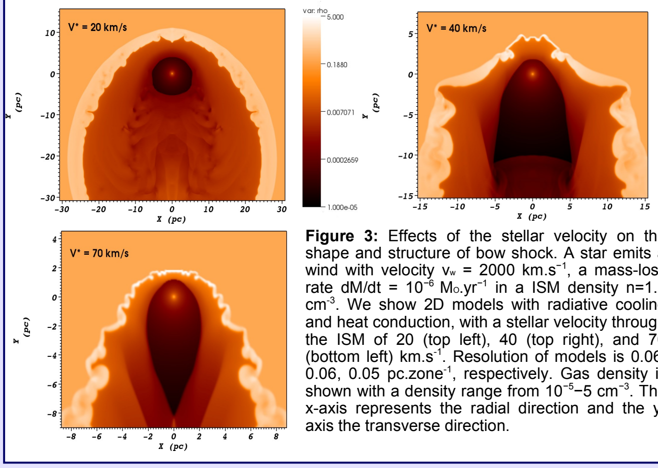

Figure 3: Effects of the stellar velocity on the shape and structure of bow shock. A star emits a wind with velocity v_w = 2000 km.s^{-1}, a mass-loss rate dM/dt = 10^{-6} M$_\odot$.yr^{-1} in a ISM density n=1.0 cm^{-3}. We show 2D models with radiative cooling and heat conduction, with a stellar velocity through the ISM of 20 (top left), 40 (top right), and 70 (bottom left) km.s^{-1}. Resolution of models is 0.06, 0.06, 0.05 pc.zone^{-1}, respectively. Gas density is shown with a density range from 10^{-5}–5 cm^{-3}. The x-axis represents the radial direction and the y-axis the transverse direction.

Bow shock modelling with the PLUTO code

Bow shocks are modelled following Mackey's method (Mackey et al., 2012), with a realistic description of the ISM including electronic heat conduction (Cowie & McKee, 1977) as well as radiative cooling. Radiative losses are modelled via a modified cooling curve (Sutherland & Dopita, 1993) for plasma under equilibrium conditions. The ISM temperature is taken as T=10000K and its density is n=1.0 cm^{-3}. We first reproduced 1D (Weaver et al., 1977) results for a structured wind bubble at rest (see Fig. 1) and 2D (Comerón & Kaper, 1998) results for a moving stellar source. We then modelled a typical O massive star (Weaver et al., 1977) moving through the ISM in order to compare the effects of the included dissipative processes on the shape of the resulting bow shock (see Fig. 2) and concluded that models with associated radiative losses and heat conduction are the most realistic. We finally effectuated a series of simulations to test the effects of stellar velocity with respect to the ISM on the shape of the correspondent bow-shocks (see Fig. 3).

For stability reasons, the numerical scheme of PLUTO has been modified following Falle (1991) affecting the way conserved quantities are treated during piece-wise linear interpolation. We have also performed scaling tests on an example bow shock simulation. The test problem is a bow shock model including radiative cooling and thermal conduction which scaling has been performed on the JUROPA supercomputer at Jülich Supercomputing Centre (see Fig. 4).

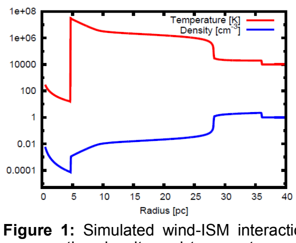

Figure 1: Simulated wind-ISM interaction, representing density and temperature as a function of the radius to the star at rest after 1.1 Myr. Wind and ISM properties are similar to Weaver et al. (1977).

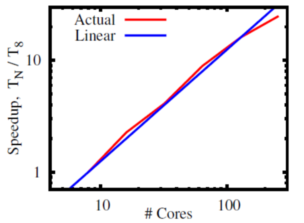

Figure 4: Speedup obtained with PLUTO on JUROPA as a function of the number of cores used (N), normalised to 8 cores.

Effects of the included physics

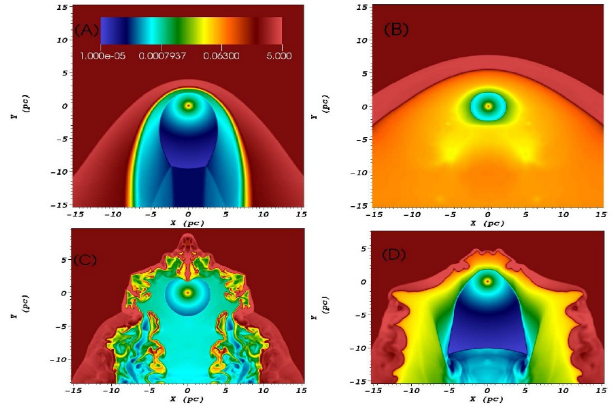

Figure 2: Effects of the included physics on the shape and structure of a bow shock for a star moving with v = 40 km.s^{-1} through the ISM and emitting a wind with velocity v_w = 2000 km.s^{-1} and mass-loss rate dM/dt = 10^{-6}Mo yr^{-1}. From top to bottom and from left to right, an adiabatic model (A), adiabatic with thermal conduction (B), with cooling (C) and with cooling and conduction (D). Resolution of model (C) is twice the other models resolution, so 0.03 pc per zones in x and y. Gas density is shown with a density range from 10^{-5}–5 cm^{-3}. The x-axis represents the radial direction and the y-axis the longitudinal direction, expressed in parsecs relative to the star.

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