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The interaction of a planetary nebula with the ISM.

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Abstract

NGC 7293, the Helix nebula, represents one of the rare instances in which theoretical predictions of stellar evolution can be accurately tested against observations since the precise parallax distance and the velocity and proper motion of the star are well known. We present numerical simulations of the formation of the Helix PN that are fully constrained by the (inferred) progenitor stellar mass, stellar evolution history, and star-interstellar medium (ISM) interaction. We have followed the evolution of the star from the early Asymptotic Giant Branch (AGB) phase to the PN stage and modeled the density and kinematical evolution of the expanding shells considering the observed relative motion of the star. In the simulations, multiple bow-shock structures are formed by fragmentation of the shock front where the direct interaction of the stellar wind with the ISM takes place.

1 Introduction

NGC 7293 (a.k.a The Helix, PN G036.1−57.1) is one of the planetary nebula (PN) with a very good determination of its distance; 202 pc from Gaia DR3 [4]. The central star has a mass of 0.60 ± 0.02 $M_\odot$[1] and a high temperature $T_{eff} = 104\,000$ K [5] implying that the star+nebula system is in a rather evolved stage. The *Galaxy Evolution Explorer* (*GALEX*; [8]) wide field-of-view (26 arcminutes) revealed for the first time striking morphological features in the form of extended bow-shocks beyond the nebular halo ([2]).

2 Numerical simulations

The numerical simulations have been performed with the fluid solver ZEUS-3D ([10]), developed by M. L. Norman and the Laboratory for Computational Astrophysics. The computations have been carried out on a 2D spherical polar grid with the angular coordinate ranging from 0° to 180° and a physical radial extension of 3 pc. They have been run at a resolution of 1600 × 1440 zones in the radial and angular coordinates of the grid respectively (or equivalently ∼ 388 au × 0.125°). Our boundary conditions are the AGB stellar wind of a 1.5 $M_{\odot}$star and a ISM density of $n_{\rm ISM}$= 0.06 cm^3, and a relative velocity respect to its ambient medium of 40 $km\,s^{-1}$. For the post-AGB stage and PN evolution we follow the stellar wind according to the prescription given in [12] by using the post-AGB evolutionary sequence given by [14] for a hydrogen burner with solar metallicity for the assumed stellar mass.

Note that the wind velocities of the central stars of PNe are several orders of magnitude higher than those experienced during the AGB phase. For the wind temperature on the AGB we used the effective temperature of the star. During the PN stage we consider the dynamics induced by the photoionization of the gas by using the approximation implemented by [3] to derive the location of the ionization front. Radiative cooling follows the cooling curves of [11] and [6] for gas temperatures above 10^4 K and according to [7] for temperatures between 10^2 and 10^4 K. The unperturbed gas is treated adiabatically. Finally, the photoionized gas is always kept at 10^4 K, so no cooling curve is applied inside the photoionized region unless there is a shock. The simulations start at the early-AGB phase, before the onset of the first thermal pulse, and continue for 20 000 years into the PN stage [1]. The stellar time for which we run the simulations is 8.3×10^5 yr.

To model the interaction process it is fundamental to know the velocity of the object with respect of its environment, relative to its external ISM. Fortunately, the available observations of the Helix allow a good determination of the space velocity of the star. Using a radial velocity of -15 $km\,s^{-1}$for the nebula, the parallax distance of 202 pc [4] and the proper motion measurement of Gaia DR3 we determined a relative velocity of NGC 7293 with respect to its ambient medium of 37.5 $km\,s^{-1}$. The Helix star belongs to the kinematic population of the thin disk in the Galaxy and as such this velocity is consistent with the range observed for this population 10-40 $km\,s^{-1}$[7]. For the simulations we have thus set the relative velocity of of NGC 7293 with respect to its ambient medium to 40 $km\,s^{-1}$.

3 RESULTS

In Figure 1., (right panel) we show the result of the numerical simulation after 819000 yr in the AGB, and 1000 yr, after the onset of the photoionization. In the left panel we show the *GALEX* FUV filter image, which at a distance of 202 pc has a FOV of 4.23 pc. It is remarkable that both figures show bow shock structures in the direction of the movement, and that the actual size in parsec is quite similar. We conclude that the morphology of the

[1]The zero age of the PN is set at the time when the star's effective temperature reaches 10 000 K

Helix can be explained by the evolution of a 1.5 $M_{\odot}$star interacting with an ISM with a relative velocity of 40 $\mathrm{km\,s^{-1}}$. apparent multiple bow-shocks.

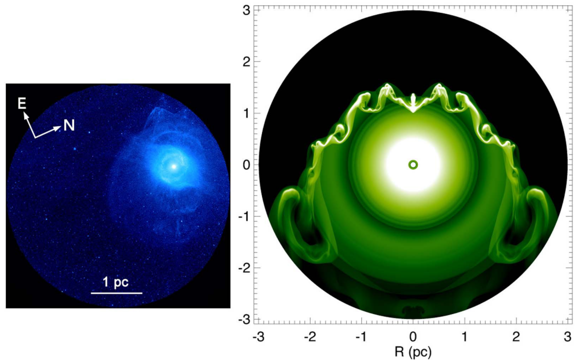

Figure 1: Left, *GALEX* FUV image of NGC 7293. At a distance of 202 pc, the FOV is 4.23 pc. Right, density map from our simulations, the snapshot corresponds to a ∼1 000 yr old PN. The morphology of the UV features is reproduced by the simulations; more important, the physical scale of the predicted structures matches the observations.

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