RevMexAA (Serie de Conferencias), **15**, 50–52 (2003)

PERCOLATING WINDS THROUGH A CLUMPY TORUS

W. Steffen and J. A. López

Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, México

RESUMEN

Mediante simulaciones hidrodinámicas con simetría axial estudiamos la interacción de un viento estelar tenue y rápido con una distribución toroidal de nubes geométricamente gruesa y de alta densidad, embebidas en un medio estacionario internubes. La densidad del gas entre las nubes decae con una ley de potencias de índice −1.9. Encontramos que el viento supersónico se percola a través del conjunto de nubes produciendo estructuras alargadas en la discontinuidad de contacto. También encontramos que la distribución toroidal de nubes es suficiente para colimar un flujo tipo chorro a lo largo del eje de simetría. Después del inicio de la interacción con el viento estelar, las colas cometarias que se forman en la región externa tienden, de forma temporal a ser cortas y huecas, mientras que éstas más tarde se convierten en largas y llenas de gas erosionado de alta densidad.

ABSTRACT

By way of axisymmetric numerical hydrodynamical simulations we study the interaction of a fast tenuous stellar wind with a thick toroidal distribution of high-density clouds embedded in a stationary intercloud medium with a power-law density fall-off of index −1.9. We find that the supersonic wind percolates through the cloud ensemble, producing finger-like structures in the contact discontinuity. We also find that such a toroidal distribution of clouds is sufficient to collimate a jet-like outflow along the symmetry axis. After the start of the interaction with the stellar wind, cometary tails in the outer region temporarily tend to be short and hollow, whereas older tails are long and filled with ablated high-density gas.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: STRUCTURE — PLANETARY NEBULAE — STARS: MASS LOSS**

1. INTRODUCTION

Fast stellar winds shape young H II regions, planetary nebulae, nebulae around symbiotic stars, and others. The structure of the nebulae is mainly determined by the composition and density distribution prior to the beginning of the interaction between the wind and the ambient medium.

The structure of the planetary nebula NGC 7293 (the Helix nebula) and others shows strong density variations as a function of distance from the central star. The inner region of the Helix nebula is void of gas and clumps; then come a few very isolated globules with cometary tails, followed by an increasing number of clouds and a denser filamentary medium as the outer edge of the nebula is approached.

The two most likely mechanisms responsable for this are photoevaporation by ionizing radiation or the interaction with a fast wind, both from the central star. Naturally, both mechanisms may be acting at the same time. One of them, however, is likely to become dominant for the destruction of the clumps (Arthur & Lizano 1997).

Dyson, Hartquist, & Biro (1993) in an analytical study and Falle et al. (2002) in a numerical simulation of the tail-formation behind a mass source find two distinct tail structures depending on the regime of hydrodynamic interaction between the wind and the flow from the source. In their studies they assume that the mass-loss mechanism does not affect the tail structure significantly. They find that in a hypersonic wind, after reaching a state of equilibrium, a bow-shock forms around the mass source and the tail of the injected flow material is wide compared to the size of the source. In the case where both flows are subsonic, long thin tails do form.

It is expected that the nebular structure, including the clumps, is not static but will evolve with time due to hydrodynamic ablation or photoevaporation. The eroded region will grow outwards such that the current radial distribution can roughly be taken as a qualitative representation of the time evolution of the nebula at a fixed distance from the central star. In this paper we extend our previous studies (Steffen & López 2003) to the case of a non-spherical toroidal distribution of clumps. This is motivated by the observation that the inner region of the Helix nebula is rather empty (as opposed to e.g., NGC 6369), indicating that the Helix nebula has a cylindrical or

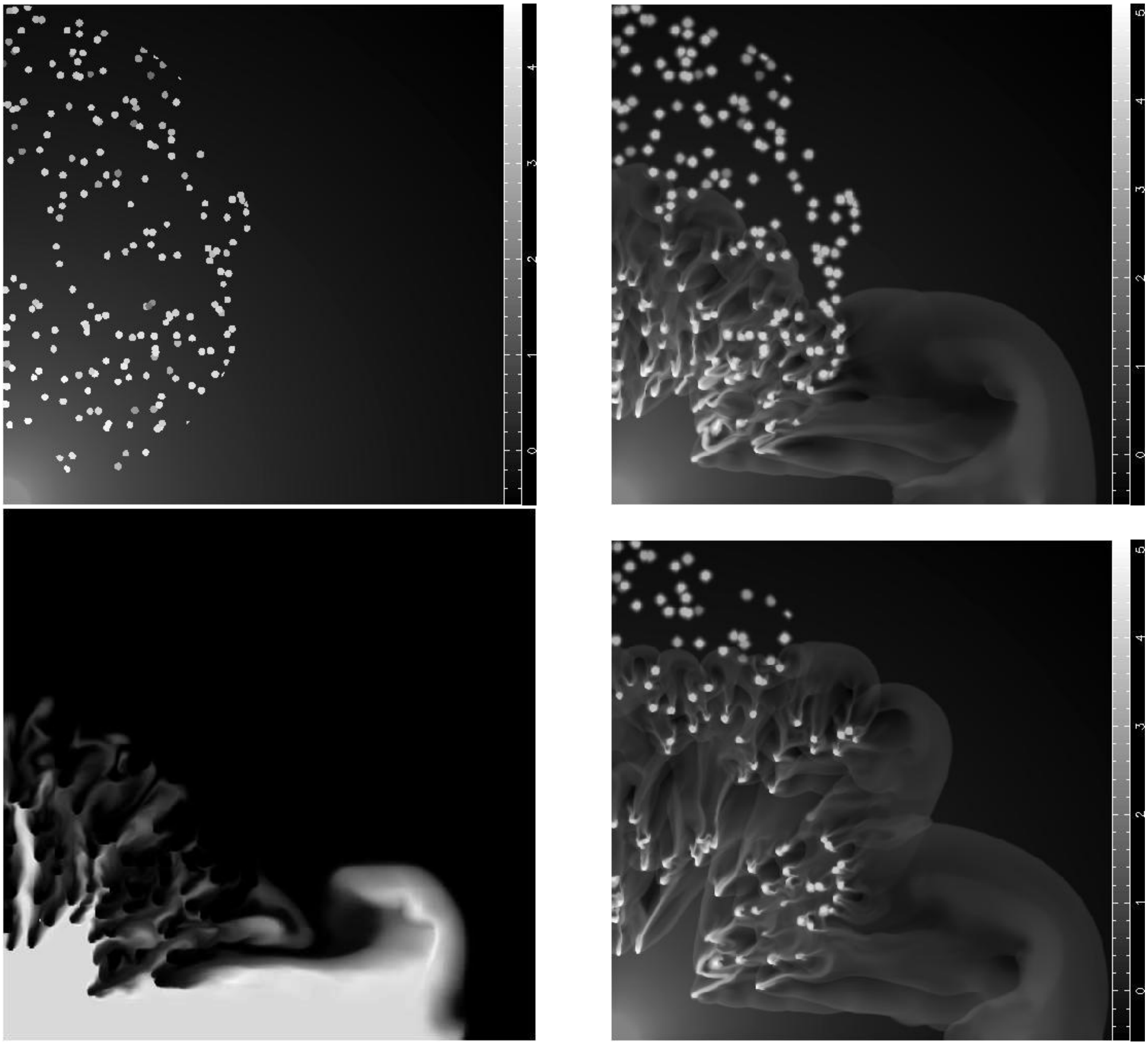

Fig. 1. The initial logarithmic distribution of number density of Run 1 is shown in the top-left panel, the same distribution after 390 years is shown in the top-right panel. The lower-left panel shows the tracer of the wind gas for the same time, and the lower-right panel shows the logarithmic distribution of number density for Run 2, with roughly half the number of clouds as compared to Run 1.

toroidal structure. As in the previous work, we consider the case of a dominant stellar wind, such that photoevaporation is not taken into account explicitly for the destruction process of the globules and clumps in the external medium.

High-resolution simulations of hydrodynamic erosion of gaseous clumps seem to indicate that this process is rather inefficient and that low numerical resolution at the scale of the clumps probably leads to an overestimate of the mass-loss rate of the globules (R. I. Klein and A. Frank: priv. comm.). Hence, our simulations, with rather low resolution at the clump scale should be regarded as a qualitative study of the flow produced by a combination of photoevaporation and hydrodynamic ablation.

In agreement with Dyson et al. (1993) and Falle et al. (2002), Steffen & López (2003) found that there are two regimes of interaction for the tails behind the clumps. First, there is the subsonic wind region which produces long wiggly tails around the clumps. Second, the direct supersonic interaction with the stellar wind, which only happens to the innermost clumps. For a shell of clouds that has a thickness comparable to the distance of its outer edge, most of the clumps are in the subsonic regime (see Arthur & Lizano, 1997, for a discussion of the differences and the possible importance of photoevaporation).

In this paper, we study the propagation of a stellar wind characteristic of planetary nebulae through a clumpy medium that is concentrated in the equatorial plane, rather than spherically symmetric. Our interest focuses on the changes in the tail structure as a function of distance from the source as well as the global structure as a function of the evolutionary state of the clumpy region.

2. SIMULATIONS

The hydrodynamical simulations have been performed using the two-dimensional code Coral (Raga et al. 1995) in its axisymmetrical mode. Cooling has been limited to temperatures above 5000 K to avoid strong cloud collapse. The gas, including the clouds, in the intercloud medium is assumed to be atomic with an average atomic mass of $m = 1.3\,\mathrm{amu}$ (Raga et al. 1995). The binary adaptive grid used is of 5 levels with 513×513 square cells at highest resolution. The physical dimensions of the simulations are in all cases 10^{18} cm, or roughly 0.3 parsecs.

We compare two simulations, which are identical except for the number and average separation of a quasi-random ensemble of spherical clouds. The clumps are distributed within a toroidal region around the star as shown in Figure 1 (top-left, large number of clouds; bottom-right, half the number of clouds).

The clouds all have a radius of 5×10^{15} cm. The densities are chosen quasi-randomly between 10 and 1250 times that of the intercloud medium at the distance of the cloud. The clumps are placed in a toroidal region between distances of 0.1 and 1 times the computational domain from the origin.

Assuming that the ambient medium was created by an AGB wind, we chose the smooth intercloud medium to have a density with a power-law dependence on the distance r from the emitting star (r^a with $a = -1.9$). The stellar wind is initialized on a sphere of radius 1/20 times the width of the computational domain with a velocity of $1000\,\mathrm{km\,s^{-1}}$ and a mass-loss rate of $2.15 \times 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$.

3. RESULTS

We find that, similar to the case of a spherically symmetric distribution of clouds, the advance of the global shock of the fast wind is inhibited in the direction of the clouds. In some regions this effect is stronger than in others, causing finger-like structures to develop. Once outside the region of clumps, these produce an irregular appearance of the outer boundary of the planetary nebula.

We also find that the cometary tails of some clumps are qualitatively different to those of others. Those near the inner edge of the clumpy zone have long, solid tails. Farther out, in the region where the wind flow is subsonic and has mixed strongly with the injected mass from the inner knots, some of the tails are split, i.e., hollow and have a marked opening angle. This splitting is transitory and an indication that the interaction with the wind has started only recently and has not reached an equilibrium state. Hence, the observation of split tails, in some cases, could help to find the position of the outer limit of the fast wind in the early stages after it started.

Along the axis of the toroidal cloud distribution, where few or no shock-retarding clouds are present, the wind propagates freely (see Fig. 1, top-right and bottom-left). This is true until an oblique shock from the side propagates all the way to the axis. This shock is caused by the interaction of the wind with the clumps that are closest to the axis and helps to collimate the axial flow. Within the region of the simulation a fairly well collimated fast axial jet is formed, which can be expected to remain collimated for some distance from the central star. Further simulations are in preparation to show the propagation of the jet further out, in order to find what sort of bipolar structures are formed in this way.

This work has been partially supported by CONACYT (grant 33660-E).

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José Alberto López and Wolfgang Steffen: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apartado Postal 877, 22800 Ensenada, B.C., México (jal,wsteffen@astrosen.unam.mx).