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MORPHO-KINEMATIC MODELLING OF GASEOUS NEBULAE WITH *SHAPE*

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RESUMEN

Presentamos una nueva herramienta para desenredar la geometría 3-D y la estructura cinemática de nebulosas gaseosas. El método consiste en combinar software comercial para animación digital para simular la estructura 3-D y el modo de expansión de la nebulosa junto con un software de representación gráfica de imágenes y perfiles de línea diseñado especialmente para el propósito. Las imágenes resultantes pueden compararse directamente con datos reales. En esta contribución presentamos resultados para la compleja nebulosa planetaria NGC 6369 basado en espectros de rendija larga obtenidos en el observatorio de San Pedro Mártir.

ABSTRACT

We present a powerful new tool to disentangle the 3-D geometry and kinematic structure of gaseous nebulae. The method consists of combining commercially available digital animation software to simulate the 3-D structure and expansion pattern of the nebula with a dedicated, purpose built rendering software that produces the final images and long slit spectra which are compared to the real data. In this contribution we show results for the complex planetary nebula NGC 6369 based on long slit spectra obtained at the San Pedro Mártir observatory.

Key Words: **PLANETARY NEBULAE: INDIVIDUAL (NGC6369) — STARS: MASS LOSS**

1. INTRODUCTION

The kinematics of gaseous nebulae expanding around a central star with spherical symmetry are easily characterized through long slit spectroscopy; in this case the spatially resolved emission line profiles show the pattern of a velocity ellipsoid. Mild deviations from spherical symmetry can be recognized through the line profile shapes with reasonable certainty from relatively simple analyses. However, in the absence of rotational symmetry, the tilt of the nebula with respect to the line of sight and the location and position angle of the slit on the nebula often result in complicated line profile shapes that are more difficult to interpret.

In recent years, the discovery of a variety of complex structures in planetary nebulae that markedly depart from rotational symmetry, such as the presence of collimated outflows, poly-polar and point-symmetric structures and rings has opened many questions regarding the origin and evolution of these objects. The correct interpretation of their 3-D geometry and kinematic structure is key to the understanding of the dynamics ruling their evolution. The projected 2-D geometry of these objects on the sky are usually complex, as are the shape of their spatially resolved emission line profiles, but together they provide the key to the 3-D nebular structure.

In this paper we present a new 3-D modeling tool called *Shape* that combines the ability of commercial modeling software with a purpose built rendering module for application in astrophysical research. We exemplify the power of the this method with recent observations of the planetary nebula NGC 6369, obtained with the Manchester Echelle Spectrometer at the 2.1 m telescope of the San Pedro Mártir observatory.

2. PROBLEM DEFINITION

The projected image on the sky of an extended nebula provides bidimensional spatial information of its structure. On the other hand, the velocity field provides information regarding the radial component of the velocity vector along the line of sight and thus conveys limited but useful information on its depth or third spatial dimension. However, given that the location of a volume element of the nebula is related to the integral of its velocity, a knowledge of the full 3-D structure requires knowledge of the velocity history of that element. The simplest case occurs if the velocity is constant over most of the expansion time. This type of velocity distribution can be expected if the nebula has evolved from its origin as a consequence of a momentum driven expansion (e.g. Zijlstra et al. 2001; Steffen & López, 2004). In this case, after a sufficiently long time, the velocity becomes proportional to the distance from the center

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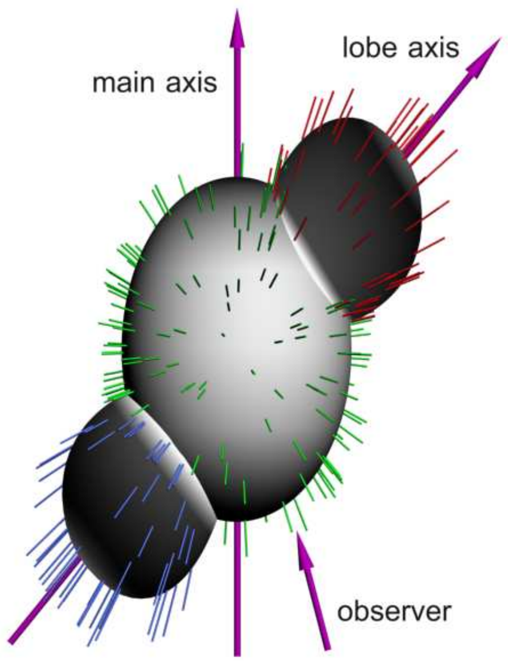

Fig. 1. 3D-structure of our model of NGC 6369 with velocity vectors shown and basic emissivity mapped on the surface.

(a "hubble-law") and the expansion of the nebula is said to be self-similar, i.e. the global shape is conserved over time.

Under these conditions, the shape of the nebula along the line of sight is mapped directly into the long-slit spectrum to within a fixed scaling factor and this has the advantage that the long-slit spectrum allows a view of the nebula from a direction perpendicular to the line of sight. If the object shows evidence for a significant degree of symmetry, the full 3D-structure and kinematics can be deduced.

Even if a simple "hubble-law" expansion is not present, the kinematics as observed in long-slit spectra often provide enough information about the 3D-structure and topology of an object, and the modeling with *Shape* can provide a good approximation to the true 3-D structure.

3. *SHAPE*

In astrophysics we are mainly dealing with complex non-linear compressible gas dynamical phenomena. Gas dynamical modeling of specific complex objects is usually not a practical aid for the interpretation of the 3D-structure of nebulae. The parameter space for the initial conditions is generally too large and ambiguous combined with long computing times for every model. It is therefore desirable to have an efficient modeling tool which helps to disentangle and interprete the kinematics and 3D-structure for the observed state of the nebula. The results can then be used for further observational or theoretical studies which may help to learn more about the formation and evolution of the object. Such a tool is also useful for the planning of observing runs by predicting observations based on one or more hypotheses for the structure and kinematics of a given nebula. In addition, a large variety of long-slit profiles can easily be compiled into catalogues and animations of spectra by varying parameters of the object or its orientation quasi-continuously. This is helpful while searching for a solution to a particular object. Furthermore, it is useful in the process of learning the interpretation of long-slit spectra for researchers or students which are not familiar with this kind of observation. In this section we describe our new version of the code *Shape* as a tool to attack these problems.

Originally *Shape* was based on the simulation of structure and kinematics using parametric geometrical equations on a regular 3-D grid (Steffen et al. 1996). This code was adapted with a simple graphical interface by Harman et al. (2004). It has been applied to a variety of objects from individual knots in planetary nebulae to complex structures in active galactic nuclei. In this paper we present the first application of a completely new version with a different approach based on particle systems rather than a regular grid.

During the last decade or so photo-realistic 3D-graphics and animation have generated a new way of producing feature films and computer games. Most of this work is based on computationally efficient mathematical representations of the visual world. However, the models do not follow the mathematics which represent the physical phenomena. The reason for this is that the solutions to the physical equations are still computationally too expensive, the exceptions being processes which can be simulated with simple mechanical forces acting on solid objects (e.g. gravity or levers). Recently, however, approximations to the physical theories of radiation transport and simple gas dynamics are emerging as part of the most sophisticated commercial software packages for 3D-modeling and animation. This trend can be expected to progress very quickly.

The modeling with these techniques is very efficient and a high degree of complexity can be achieved. However, these general purpose 3D-graphics modeling codes do not produce the spectral information from the kinematics of the model. We have therefore upgraded and adapted our code

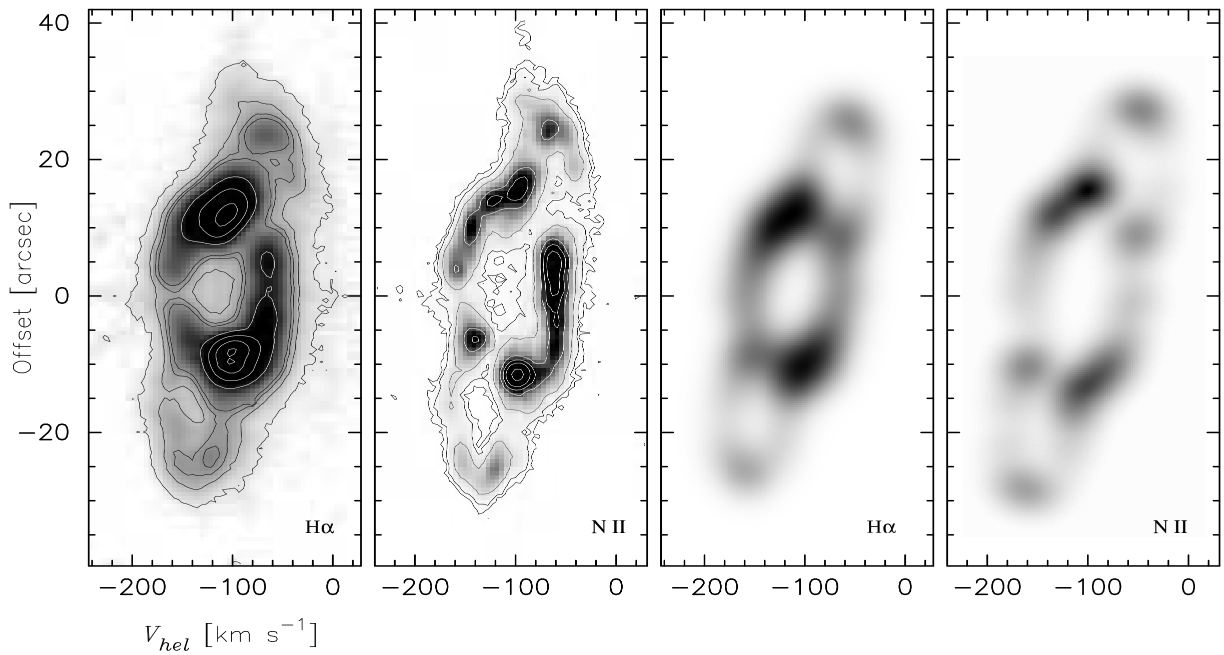

Fig. 2. Long-slit emission line profiles along the major axis of NGC 6369 (see Fig. 3). Left panels: Hα (square root gray-scale) and NII (linear gray-scale). On the right we have the corresponding long-slit spectra resulting from the *Shape* modeling.

Shape which renders the images and long-slit spectra using the information from the modeling code. A special interface has been programmed to control *Shape* from within the modeling software. This interface allows the display of the images and spectra as well as to specify the rendering parameters such as the orientation of the object with respect to the line of sight, spectral slit position and width, seeing values, spectral resolution, colors and others.

As our 3D-modeling software we use *Autodesk 3DS Max 7* (see the website *www.discreet.com* for detailed software information). We apply any available tools of the software to create a particle and velocity distribution in space and time in order to model an object. In particular we use the *ParticleFlow* particle system to generate particle distributions which are then exported and rendered in *Shape* . Note that the code does not perform any physical radiation transport or line emission calculation based on the physical conditions in space. What it does is to directly assign a relative emissivity distribution.

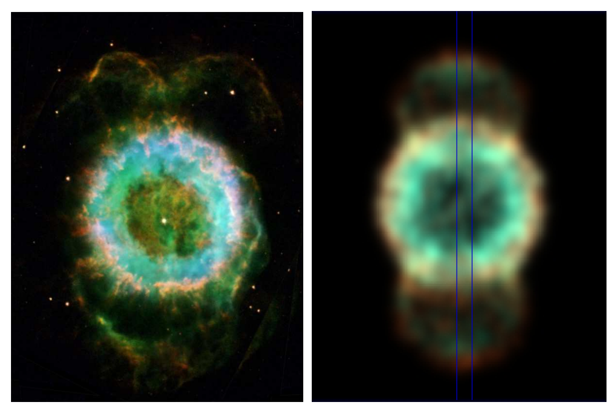

Fig. 3. Hubble Space Telescope observation of NGC 6369 (left, Hubble Heritage Team, NASA) and our image composing the Hα in green/blue with NII in orange rendered at a resolution corresponding to approximately 0.3″. The long-slit position is marked with two lines (see electronic version of this article for color figure).

4. OBSERVATIONS AND MODEL RESULTS FOR NGC 6369

For the modeling of NGC 6369 we have used an initially spherical shape and deformed it such that it matches our initial estimate of the 3D-shape according to the image and spectrum. We then applied a brightness map to the surface which approximates the proposed emissivity distribution from the Hα and NII emission lines. This brightness distribution is then used to control the number density of particles on the surface. The structure and emission distribution is then adjusted manually until a satisfactory match is found. In a forthcoming paper we will give a more detailed description of the modeling approach in general and to this particular object. Here we present our preliminary results. The long-slit data were obtained with MES on the 2.1 m telescope at the San Pedro Martir Observatory. The spectral resolution is 10 km s^{-1} and the spatial resolution 0.6 arcsec along the slit.

Monteiro et al. (2004) proposed a "diabolo"-type structure for NGC 6369 based on the analysis of spectral imaging data of a number of ions. The diabolo model implies a narrow waist in the equatorial plane with its symmetry axis close to the line of sight. With this orientation such a narrow torus-like waist is expected to have very low velocity along the line of sight and in the Hα longslit spectrum of it should appear as a feature near the systemic velocity. The observations presented in Figure 2 do not show clear evidence for a narrow low-velocity waist. However, bright emission regions near the systemic velocity in the line profiles are apparent. In our model this is due to both, mild intrinsic equatorial enhancement as well as a long tangential line of sight through the spheroidal main nebula (see Figure 1). The model does not require a waist.

The observed spectra (Figure 2, left) show that the central "barrel" and the "ears" are connected and probably conform a single topological closed surface. Our modeling shows, that our line of sight is very near the main symmetry axis (tilt $\approx 15°$) and the axis of the lobes (ears) is tilted approximately $40° \pm 10°$ with respect to the main axis. More detailed observations and modeling might improve that figure. Similarly, the ratio between the length to radius of the barrel is not well constrained by the current modeling and observations. We estimate that it is of the order 3/2.

We have run two expansion configurations. Based on the observation that the highest and lowest projected velocities in the spectra are similar for the barrel and the ears, we considered a constant velocity with the direction perpendicular to the surface. This corresponds roughly to an energy driven bubble (in this case three different bubbles, the barrel and the two ears). In this case we did not find any reasonable shape that would be similar to the image and spectra simultaneously.

The second model assumes that the velocity is proportional to distance and the direction of motion is radial from the center of the nebula. The resulting surface model with representative velocity vectors is shown in figure (1). The rendered image and spectrum are shown in figure (2). For the Hα emission we assume that emission comes from a region somewhat inside this surface and for NII slightly outside, with some overlapping around the surface that is shown (as seen in the observed spectra and images). The particle number density is proportional to the brightness on the 3D-surface (1), which is not accurately represented in the image due to lighting effects of this visualization.

We find that the model with the velocity law proportional to distance produces an acceptable fit to the observed image and spectrum. This suggests that this flow is in a relaxed momentum driven state, including the ears, which do seem to move somewhat slower than expected from this expansion law. However, this has to be confirmed by further observations and modeling. This might be an indication for a short-lived event, which is not acting on the ears anymore, and/or a stronger interaction of the "ears" with the ambient medium due to their lower densities. A similar event at the brink of exiting the main nebula seems to have been observed in several other PNe, like KjPn8, where the nebula and the tilted collimated event have their axes near the plane of the sky (López et al. 2000). Other similar nebulae are NGC 6886 and NGC 6565 (Turatto et al. 2002).

In conclusion, we propose that the basic structure of NGC 6369 is that of a spheroidal or barrel-shaped main nebula with bipolar extrusions at a large angle to the symmetry axis of the main nebula.

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