

NGC 7027: Probing the kinematics and excitation conditions of the warm molecular gas

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Abstract. Tracking the mass-loss history of planetary nebulae (PNe) by means of molecular emission lines (mainly mm and sub-mm ranges) is fundamental to gain insight into the mechanism of nebular shaping. This is particularly important in cases such as NGC 7027, where most of the nebula is constituted by molecular gas (85% of a total of 1.4 M_⊙, see Fong *et al.* 2001).

To this aim, Herschel/HIFI provides an invaluable tool to probe warm molecular gas (~50–1000 K). It produces 1-D, high resolution spectra of the whole nebula (convolved with the telescope beam) in high-excitation molecular transitions (e.g. CO $J=6-5$, $10-9$ and $16-15$). Although the morphological information is therefore lost, the kinematics and the excitation conditions can be studied with unprecedented detail (see Bujarrabal *et al.* 2011).

We have developed a code, **shapemo1**, which, used along the existing **SHAPE** software (Steffen *et al.* 2010), implements spatiokinematical modeling with accurate non-LTE calculations of line excitation and radiative transfer in molecular species. The high quality of the data, together with this code, have allowed us to study, for the first time, the kinematics and excitation conditions of the warm gas of a PN with such a high-excitation.

Keywords. planetary nebulae: individual (NGC 7027), ISM: kinematics and dynamics, radiative transfer, molecular data, submillimeter

The Matryoshka Model. We have built a relatively simple model of the molecular gas of NGC 7027. It consists of three nested, mildly bipolar shells and a pair of high-velocity polar blobs. Since our data lack any information on the geometry of the nebula, we have imposed similar distance, morphology and orientation to those found in other studies in low-excitation CO or H₂ emission (e.g. Nakashima *et al.* 2010). For each shell, we have assumed a velocity field composed of (*a*) a radial, constant component plus (*b*) a constant axial component which is triggered for distances to the nebular equator greater than 1".

The synthetic profiles of our resulting preliminary model of the ¹²CO $J = 2-1$, $6-5$, $10-9$ and $16-15$ lines are shown in Fig. 1, along with the observations; the model parameters are shown in Table 1.

Modelling process: SHAPE and shapemo1. We have used a special ($\beta 4.51$) version of **SHAPE**, specifically tailored for usage alongside our own GDL/IDL-based code, **shapemo1**. The process is as follows: **1.** We model the nebula in **SHAPE** and produce a text file with the position, velocity, density and temperature of each cell in the grid. **2.** **shapemo1** reads the text file. The user selects the desired molecular species and transition, the molecular abundance X and the local value of the microturbulence. **shapemo1** then uses accurate non-LTE calculations of line excitation (based on the LVG approximation) to compute

Table 1. Model parameters. v_0 denotes the expansion velocity outwards from the central star; v_z is the additional component along main axis. Assumed distance to the PN is 1 kpc.

Shells	r_{polar}	$r_{\text{equatorial}}$	thickness	v_0 (km s ⁻¹)	v_z (km s ⁻¹)	$X(^{12}\text{CO})$	ρ (cm ⁻³)	T (K)
Inner shell	9''	5''	0''5	13.0	7.5	7×10^{-5}	1.3×10^5	$\gtrsim 200$
Medium shell	10''5	6''5	1''5	9.75	5.6	6×10^{-4}	2.5×10^4	80
Outer shell	12''	8''	1''5	9.75	5.6	6×10^{-4}	2.5×10^4	40

Blobs	distance to star	radius	v_0 (km s ⁻¹)	v_z (km s ⁻¹)	$X(^{12}\text{CO})$	ρ (cm ⁻³)	T (K)
Polar Blobs	4''6	1''5	-	40	6×10^{-4}	1.5×10^5	$\gtrsim 200$

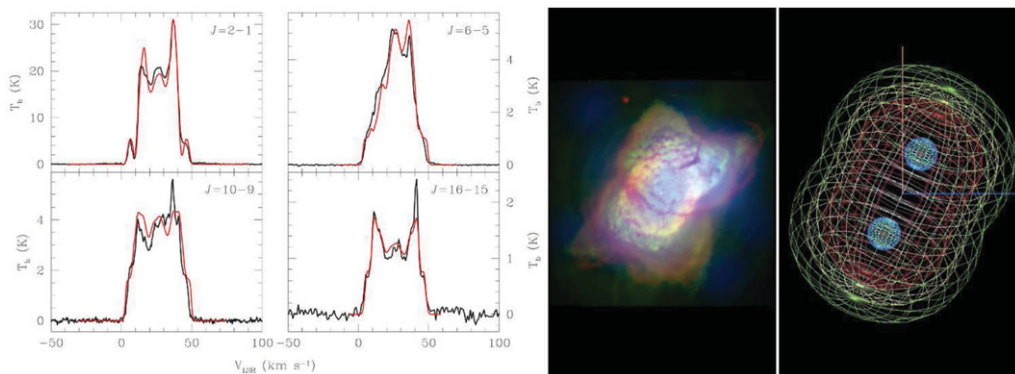


Figure 1. *Left:* Resulting synthetic spectra (red) and observations (black) for 4 different ¹²CO transitions (the $J=2-1$ data is from the IRAM 30m radiotelescope). *Right:* Composite HST NICMOS/WFPC2 image of NGC 7027, from Latter *et al.* 2000; and SHAPE mesh of the Matryoshka model of the molecular gas of NGC 7027 (approximately to scale).

the absorption and emission coefficients of each individual cell in the grid. **3.** SHAPE reads the text file produced by `shapemol` and performs full radiative transfer solving for the selected transition. After convolving the resulting datacube with the simulated telescope beam, it generates a 1-D spectrum to be compared directly with the observations.

Concluding Remarks. The inner shell, located just beyond the photodissociation region (PDR) has significantly lower abundance, higher density, and hotter temperature ($T \gtrsim 200$ K) than the other two. Furthermore, its velocity is 25% greater, which is indicative of a front shock traveling outwards through the nebula, in a similar way as the low-velocity shock front found for instance in CRL 618 (e.g. Bujarrabal *et al.* 2010), in which a double shell is expanding against the nebular halo. This shock front, along with the high-velocity blobs, is likely to have major implications on the shaping of the nebula. For a refined version of the model and further discussion, see Santander-García *et al.* (in preparation).

References

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