AN INFRARED/MILLIMETER STUDY OF THE DUMBBELL NEBULA

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ABSTRACT

We report preliminary results of a study at infrared and millimeter wavelengths of the Dumbbell nebula carried out with ISO and the IRAM 30-meter telescope. These observations bring to light a complete image of a prototypical evolved planetary nebula, from the bright innermost ionized region to the dark external molecular envelope.

Key words: ISO – Planetary nebulae: individual (NGC 6853) – Infrared: ISM: lines and bands – radio lines: ISM

1. INTRODUCTION

The Dumbbell Nebula (M27, NGC 6853, PN G060.8-03.6) is a prototypical evolved planetary nebula (PN) and one of the nearest known (with an estimated distance of 380 pc, Harris 1997). Classified as a late elliptical (size about 8′ × 5′), the morphology of the Dumbbell is complex displaying a central irregular bar, multiple arcs and shells and a weak halo. The temperature of the central exciting star is estimated to be ~ 120,000 K and the nebula is carbon-rich.

Mapping the millimeter rotational lines of CO provides many details on the structure and kinematics of PNe envelopes (e.g., Bachiller et al. 1993). Infrared observations are powerful tools to study the different regimes in PNe, from the innermost ionized region to the molecular envelope traced by H_2 emission lines (e.g., Cox et al. 1998). In this paper we report high-sensitivity imaging and spectroscopy at infrared and millimeter wavelengths of the Dumbbell which substantially improve our knowledge of this nebula and more generally of the processes of evolved PNe. A complete report of our work will appear elsewhere (Bachiller et al. 2000).

2. OBSERVATIONS

Infrared observations were carried out with the ISO satellite in May 1996. Images were obtained with the ISOCAM instrument in two filters, LW2 (5–8.5 μm) and LW3 (12–18 μm). With a pixel size of 6″, the camera field is 3′ × 3′ (32×32 pixels). The extent of the optical nebula was covered with a raster map of 6×6 frames with an overlap of half a frame for each raster position. The resulting images are shown in Figure 8, together with ground-based images in the H_2 1–0 S(1) line and in [OIII].

Far-infrared spectra were obtained with the Long Wavelength Spectrometer (LWS) in full grating mode (LWS01 AOT). This configuration provides coverage of the 43-196.7 μm range at a resolution R = $\lambda/\Delta\lambda$ ~ 140-330. Five positions were observed along the nebular waist (Figure 9). Mid-infrared spectro-imagery was obtained using the ISOCAM circular variable filter (CVF) in two fields covering the NE and the SW quadrants of the nebula. The spectra covered the wavelength range from 5.0 to 16.6 μm, with an effective spectral resolution of R ~ 40.

The CO mapping of the Dumbbell was carried out in 1992-1993 using the IRAM 30-meter telescope on Pico Veleta, Spain. The CO(1–0) and CO(2–1) lines were observed simultaneously. The telescope beam size is 22″ at 115 GHz and 12″ at 230 GHz. Pointing is estimated to be accurate within ~ 4″.

3. STRUCTURE OF THE NEBULA

8.1. The ionized nebula

The ionized nebula is well traced by the LW3 image (Figure 1) which is dominated by the emission of the [NeIII] 15.5 μm line as shown by the ISOCAM CVF spectral data. This is further confirmed by the similarity between the LW3 and optical [OIII] images (see Figure 1). The nebula appears as a spheroidal shell, opened toward the NW and the SE and with an inner cavity. The maximum emission is concentrated in the inner part of the equatorial region.

In the LWS spectra, the ionized region is traced by the [OIII] (51.81 and 88.36 μm), the [NIII] (57.33 μm) and [NII] (121.90 μm) fine-structure lines. All these lines peak near the center of the nebula. The ratio of the [OIII] lines provides an estimate of the electronic density, almost independent of the electronic temperature. Using the calculations of Rubin et al. (1994), we obtain n_e ~ 100 cm^{-3} in good agreement with estimates based on optical studies. A preliminary analysis indicates that the total mass of the ionized region, derived from the intensity of the 88 μm line, is ~0.3 $M_\odot$.

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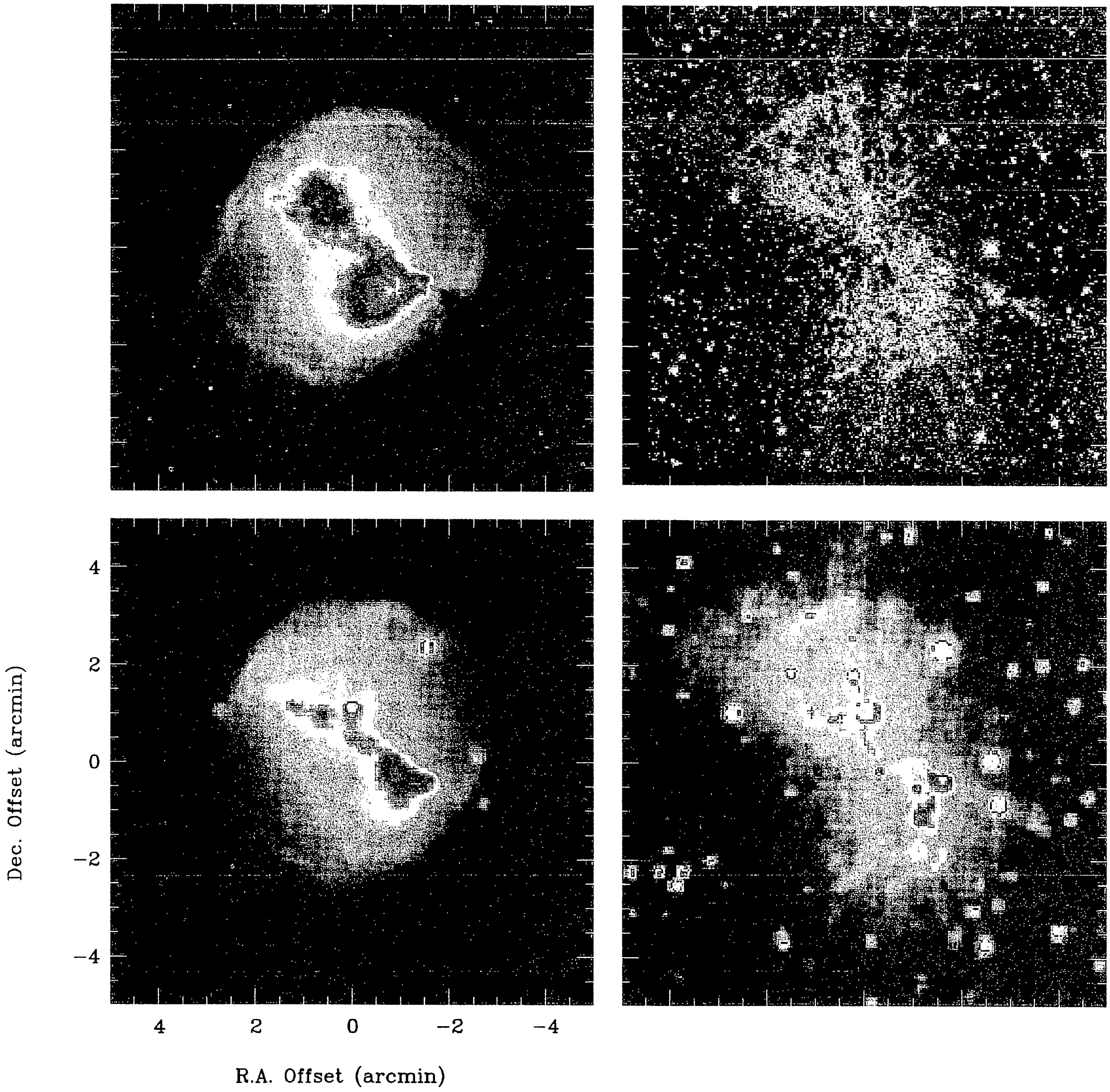

Figure 8. Images of the Dumbbell Nebula. Bottom left: ISOCAM LW3 image. Bottom right: ISOCAM LW2 image. Top left: Optical [OIII] image from Manchado et al. (1996). Top right: H_2 image at 2.12 μm from Kastner et al. (1996).

8.2. The Photodissociation Region

In photodissociation regions (PDRs), the molecular hydrogen is mainly excited non-thermally by absorption of UV photons followed by UV fluorescence and infrared radiative cascade (e.g., Natta & Hollenbach 1998). The H_2 infrared emissions lines are thus prime tracers to study the structure of PDRs and to derive the temperature and column density of the excited molecular gas. As in the case of the Helix nebula (Cox et al. 1998), the LW2 image of the Dumbbell is dominated by the emission of the pure rotational S(5) emission line of H_2 (this result follows from the analysis of the CVF spectra - see Bachiller et al. 2000 for a detailed discussion). This is further corroborated by the striking similarity between the ground-based H_2 image and the LW2 image. In both images, the emission is seen along a kind of extended waist surrounding the equatorial region, with ray-like or cometary structures pointing toward the center of the nebula.

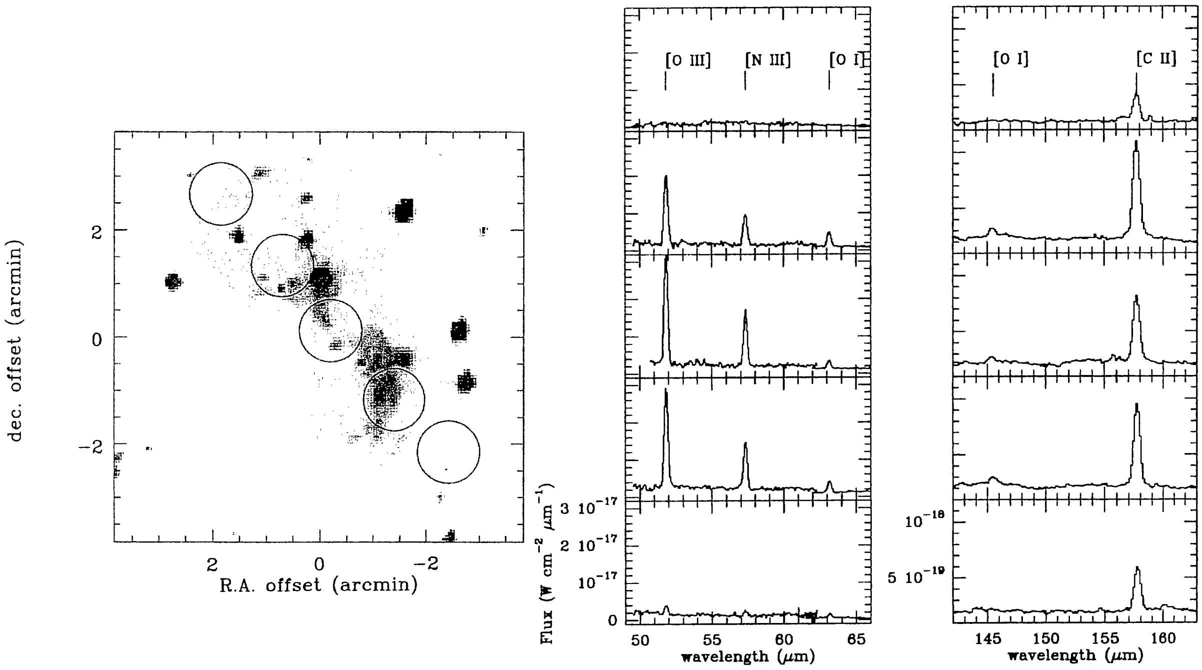

Figure 9. Left panel: the positions where LWS spectra were obtained are shown as circles on the LW2 image. The circle size corresponds to the LWS beam. Right panels: two representative portions of the LWS spectra are shown, ordered from SW to NE when one moves from bottom to top. In total seven fine-structure lines are detected: [OIII] (51.8 and 88.3 μm), [NIII] (57.3 μm), [NII] (121.9 μm - not displayed) for the ionized gas, and [OI] 63.2 and 145.5 μm) and [CII] (157.7 μm) for the PDR. No molecular bands are detected. A weak continuum is also observed, which corresponds to dust emission at a temperature of ~60±20 K.

The PDR interface is also traced by strong emission in the atomic fine-structure lines of [OI] (63.18 and 145.53 μm) and [CII] (157.74 μm) (Figure 2). The intensities of these lines peak where the H_2 emission is strongest and are systematically weaker near the central position where the ionized gas dominates. This behaviour is consistent with a configuration in which the PDR is distributed in a surrounding shell.

[OI] and [CII] lines, which are the main coolants of PDRs, provide valuable information about the physical conditions in this region. We find that the PDR associated with the Dumbbell has a density of $\sim 10^4$ cm^{-3}, and is illuminated by the stellar FUV flux of $G_o \sim 16$ (in units of ISRF = 1.6×10^{-3} erg cm^{-2} s^{-1}). From the extent of the PDR and the [CII] line intensities, preliminary estimates indicate that the mass of the PDR is ~ 0.05 $M_\odot$.

Finally, we note that the ISOCAM CVF data indicate the presence of weak and unusual dust bands. The spectral signatures appear to originate from small aromatic molecules, although the mid-infrared bands are clearly distinct from the standard spectrum observed in the interstellar medium. This could be a result of the extreme excitation conditions in the Dumbbell. A further discussion of these results will be given elsewhere (Cox et al. in preparation).

8.3. The molecular envelope

The molecular envelope, traced by the CO (J=2–1) line, is shown in Figure 10. The CO emission forms a complex filamentary structure consisting of bright clumps which are interconnected with weaker emission. The main filament follows the bright bar seen in optical and infrared images similar to the H_2 image (Figure 1).

The CO line profiles are split by about 58 km s^{-1} toward the central region of the Dumbbell nebula, but this splitting decreases when one moves away from the center (see Figure 11). Such spectral line splitting is common in PNe and usually results from hollow expanding structures. In the case of the Dumbbell, the approaching part of the hollow structure is seen at (blueshifted) velocities ranging from −54 to −27 km s^{-1}, whereas the receding part is seen at (redshifted) velocities ranging from −12 to 9 km s^{-1}. The expansion velocity is estimated to be ~29 km s^{-1}.

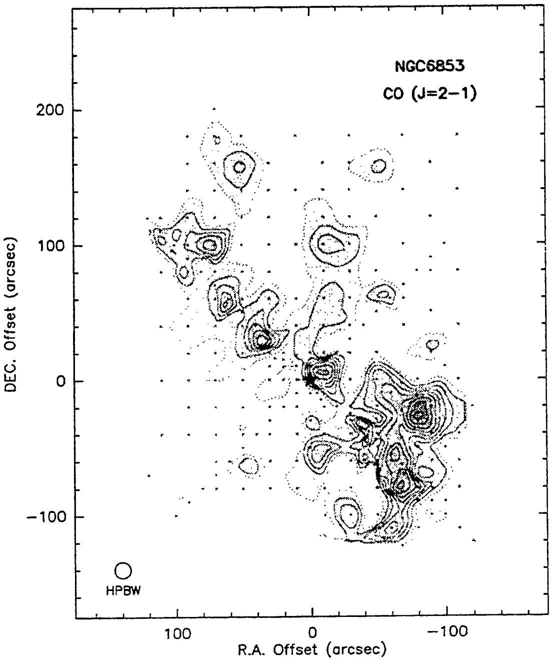

Figure 10. Integrated intensity map of the CO(2-1) line in the Dumbbell Nebula. First contour (dashed line) and step are 1 K km s^{-1}. The central position is indicated by a filled star. Dots indicate the observed positions.

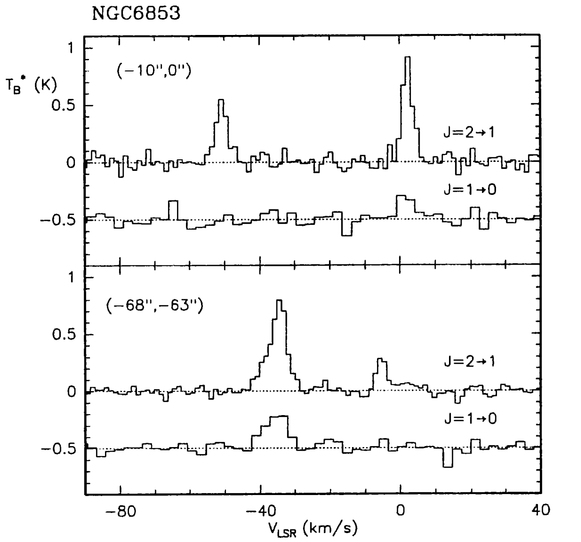

Figure 11. CO line profiles toward two positions of the Dumbbell. Offsets are in right ascension and declination with respect to the central position of Figure 10.

Thus, taking into account the correction for projection effects, the expansion velocity of the molecular envelope is found to be comparable to the expansion velocity of the main optical shell (~30 km s^{-1}).

The kinematical structure indicates that the molecular shell consists of a ring of radius about 0.25 pc. This shell is made of molecular clumps, many of which appear as striking cometary structures observed in H_2 images (Figure 1). The kinematic timescale of this shell is 8×10^3 yrs. From the CO data, the mass of the molecular ring is estimated to be ~0.01 $M_\odot$ which represents ~ 3% of the ionized mass in the nebula.

4. CONCLUSION

The combination of infrared and millimeter observations provides a complete view of the Dumbbell by probing the ionized central region, the photodissociation region and the molecular ring. The availability of both imaging and spectroscopic results, together with the kinematical information from the CO observations, allows us to study the connections between these different gas phases in the extreme environments of the Dumbbell nebula. This set of data is useful to test our current views on the physical conditions in PDRs associated with evolved planetary nebulae. In particular, the excitation of the molecular hydrogen and the nature of the carbon-rich dust particles can be studied in detail in the Dumbbell and be compared with the results obtained on the slightly more evolved Helix nebula.

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