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H_2 MORPHOLOGY OF YOUNG PLANETARY NEBULAE

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ABSTRACT

The distributions of H_2 1–0 $S(1)$ emission in the young planetary nebulae BD +30°3639 and NGC 7027 show striking similarities: both have limb-brightened arcs of H_2 emission with radii that are about twice those of their H II regions. The extended H_2 emission in both nebulae is attributed to a photodissociation region. This implies that the neutral envelopes of these young planetaries extend well beyond the edge of the H II region, in contrast to older nebulae where the ionized and molecular gas are more nearly coextensive. The contrast between young and old planetaries can only be explained if the molecular envelope is inhomogeneous. We endorse a scenario for the evolution of a planetary nebula in which a photodissociation front propagates through the clumpy molecular envelope, leaving the ionized core embedded in an envelope of partially ionized atomic gas and dense molecular knots. In an evolved planetary, the H II region has expanded to engulf some of the dense molecular knots, which can be identified with bright [O I] and H_2 1–0 $S(1)$ condensations, while the remnant of the photodissociated envelope may be detected as a faint optical halo.
Subject headings: ISM: molecules — planetary nebulae: general —
planetary nebulae individual (BD +30°3639, NGC 7027)

1. INTRODUCTION

The planetary nebula NGC 7027 was among the first detected sources of vibrationally excited H_2 emission (Treffers et al. 1976). It is now clear that H_2 emission is a common feature of planetary nebulae (Isaacman 1984; Storey 1984; Webster et al. 1988; Geballe, Burton, & Isaacman 1991). It has also become increasingly clear, since the detection of CO (1–0) in NGC 7027 (Mufson et al. 1975), that mm wavelength molecular lines are important tracers of the neutral envelopes of planetary nebulae. Low-resolution mapping of planetary nebulae shows that the H_2 emission closely follows, but tends to be more extended than, the optical emission that traces the ionized gas (Beckwith, Persson, & Gatley 1978; Beckwith et al. 1980; Zuckerman & Gatley 1988; Webster et al. 1988). Higher resolution H_2 imaging of NGC 6781 shows that the excited molecular gas is located just beyond the edge of the ionized gas (Zuckerman et al. 1990). High-resolution CO mapping of planetary nebulae also shows that the distribution of molecular and ionized gas is closely related (Bachiller et al. 1993).

By contrast, the CO and H_2 morphologies of NGC 7027 are very striking, and qualitatively different from those already mapped. The H II region lies in a cavity at the center of a large molecular envelope (Bieging, Wilner, & Thronson 1991; Graham et al. 1993). The H_2 emission consists of two components; an inner shell of H_2 emission that is coincident with the outer edge of the H II region; a detached outer shell of emission that loops around the H II region with four-fold symmetry (Graham et al. 1993). The outer loop of H_2 emission bridges the gap between the H II region and the inner edge of the CO envelope, and is identified with a photodissociation front. The H_2 knots associated with the H II region are dense clumps of molecular gas with sufficient column depth to have survived the passage of the photodissociation front (Graham et al. 1993).

The H_2 emission from planetary nebulae has generally been attributed to shocks driven into the neutral envelope by the expansion of the H II region (Beckwith et al. 1980; Zuckerman & Gatley 1988). By contrast, for NGC 7027, Graham et al. (1993) find no evidence for shock excitation by comparing the H_2 and CO kinematics, while arguing that the morphological relationship between H_2, 3.28 μm PAH emission, and CO strongly favor a photodissociation region interpretation. Several authors have discussed the contribution of UV pumping to H_2 excitation in planetary nebulae (e.g., Black & van Dishoeck 1987; Dinerstein et al. 1988; Genzel, Harris, & Stutski 1988; Sternberg & Dalgarno 1989), and Tielens (1993) has recently stressed the relevance of photodissociation regions to planetary nebula evolution. Tielens describes a scenario in which the neutral envelope is inhomogeneous. When the ionizing source from the central star is switched on a photodissociation front races through the interclump gas leaving only dense knots in molecular form. Clumps with $N_H \gtrsim 2 \times 10^{22}$ cm^{-2} survive the entire planetary nebula phase.

New observations of BD +30°3639 show that the H_2 morphology is similar to that of NGC 7027, in that both have a detached arc of H_2 emission. We discuss the H_2 morphology of NGC 7027 and BD +30°3639 within the context of the photodissociation region model, and argue that in these young planetary nebulae photodissociation fronts are currently propagating through the interclump molecular gas in the neutral envelope.

2. OBSERVATIONS

BD +30°3639 was observed on 1990 May 7 at the Palomar 200 inch telescope using a camera equipped with a 58 × 62 InSb detector array. The seeing at 2 μm was ≃0\".7. Images were obtained at 2.09, 2.12, 2.17, and 2.21 μm with a $\Delta\lambda/\lambda$

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$\simeq 1.3\%$ circular variable filter. The 2.12 μm setting includes emission from H_2 1–0 $S(1)$ 2.1218 μm and He I ^3P–^3S 2.114 μm, while the 2.17 μm setting covers Brγ at 2.1661 μm. The 2.09 and 2.21 μm settings are free of bright emission lines.

3. RESULTS

The Brγ 2.17 μm emission forms an unbroken elliptical shell with brightness enhancements to the north and south (Fig. 1, [Pl. L10]). The emission is virtually identical to the 15 GHz map of Masson (1989b). At 2.12 μm the free-free continuum from the H II region is prominent, but there is a ridge of emission to the east, beyond the edge of the H II region, at a distance of 4″ from the central star. Fainter emission extends to a diameter of 12″. Neither of these features is present at either Brγ or continuum wavelengths, and is therefore due to line emission. Within the H II region the 2.12 μm image traces a blend of H_2 and He I, but only H_2 beyond the edge of the ionized gas.

To emphasize line emission, the 2.09 μm off-line image was subtracted from the on-line images (see Fig. 1). This image clearly shows an arc of H_2 emission that is detached from the H II region. The 2.21 μm data unfortunately suffers from additional noise, and therefore a more accurate continuum-subtracted line image cannot be made by interpolating the continuum between 2.09 and 2.21 μm. Consequently, the H_2 line surface brightness is unreliable where the continuum is strong, i.e., in the H II region. The equivalent width of Brγ is large. Therefore, this line flux is accurate.

Comparison of the current data with the single beam measurements of Beckwith et al. (1978) suggests that most of the H_2 emission measured in their 10″ diameter beam comes from the extended component, rather than from the H II region. We cannot show this directly because the continuum subtraction for the H_2 image is unreliable within the H II region. However, measuring the H_2 flux within an annulus between 7″.5 and 10″, centered on the central star accounts for $\simeq 70\%$ of the flux found by Beckwith et al. (1978). This conclusion is consistent with the observations of Geballe et al. (1991) who measured the H_2 1–0 $S(1)$ flux in a 5″ beam, and find 34% of the flux in a 10″ beam.

4. THE NEUTRAL ENVELOPE

The H_2 emission in BD +30°3639 extends several arc seconds beyond the edge of the H II region, forming a roughly elliptical area of 8″ × 12″. Thus, a straightforward implication of Figure 1 for BD +30°3639 is that the molecular envelope of this planetary nebula reaches significantly beyond the edge of the H II region to a radius of at least 6″. This result confirms CO (1–0), (2–1), and Na I D observations that the size of the neutral envelope of BD +30°3639 is almost twice that of the H II region (Dinerstein & Sneden 1988; Bachiller et al. 1991, 1992).

Figure 1 compares the H_2 morphology of BD +30°3639 and NGC 7027 and shows that both planetary nebulae have extended limb-brightened arcs of H_2 1–0 $S(1)$ emission, with a size exceeding that of the H II region. The brightest part of the outer shell of H_2 emission is aligned along the major axis of the H II region in both cases.

BD +30°3639 and NGC 7027 are similar because they have neutral envelopes that extend significantly beyond the edge of the ionized gas. BD +30°3639 and NGC 7027 are therefore distinct from most planetary nebulae mapped to date, where there is a close spatial association of H_2, CO and the ionized gas (Beckwith et al. 1978; Zuckerman & Gatley 1988; Webster et al. 1988; Zuckerman et al. 1990). It is likely that the difference arises because, compared to BD +30°3639 and NGC 7027, the planetaries that have been observed are large, low surface brightness, evolved nebulae such as NGC 6720 and NGC 6781 (Beckwith et al. 1978; Zuckerman & Gatley 1988; Bachiller et al. 1989, 1993).

The distribution of H_2 emission in BD +30°3639 is nonuniform, being much brighter to the east than to the west. This asymmetry is unexpected, given the symmetry of the H II region. The H_2 morphology of BD +30°3639 is much more asymmetric than that of NGC 7027. The eastern H_2 emission forms a distinct bright patch. The east-west asymmetry is quite marked: the eastern lobe is $\gtrsim 4$ times brighter than the corresponding region on the western side of the H II region. Similar asymmetry is present in the distribution of light scattered in the Na I resonance D lines (Dinerstein & Sneden 1988). The peak Na I D surface brightness coincides with the eastern peak of H_2 emission 4″ east of the central star, and, at positions between 3″ and 5″ west of the central star, the Na I D emission is up to a factor of 2 weaker than at the equivalent positions on the east side. BD +30°3639 is the only planetary nebula with detected 21 cm H I emission; the bulk of which is unresolved in a 11″.5 × 23″ beam (R.A. × Decl.). However, there is a suggestion in the data that the H I emission extends at low surface brightness to the east (Taylor, Gussie, & Pottasch 1990).

The east-west asymmetry in H_2 and Na I D emission in BD +30°3639 may reflect an asymmetric distribution of neutral material in the circumstellar envelope. The asymmetry may arise because the material to the west is not molecular, or simply because there is less material in that direction. Ionization and photodissociation will occur most rapidly along directions where the column density is lowest. Thus, the observed asymmetry is almost certainly due to an asymmetric mass loss distribution from the progenitor. Nonuniform illumination by the central star is a seemingly unlikely alternative.

5. UV EXCITED H_2 EMISSION IN BD +30°3639

Graham et al. (1993) have attributed the H_2 emission from NGC 7027 to a photodissociation region. This interpretation is consistent with: the CO and H_2 kinematics; the morphological relationship between the CO, H_2, and the 3.28 μm PAH emission; and the H_2 surface brightness (Graham et al. 1993). The peak, dereddened, H_2 emission in the outer loops of NGC 7027 and BD +30°3639 is very similar: $I_{1-0\,S(1)} = 1.6 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1} and $I_{1-0\,S(1)} = 1.7 \times 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}, respectively. The molecular gas density and the UV field strength in both planetary nebulae are similar (see below), and therefore it is likely that the extended halo of H_2 emission in BD +30°3639 is also due to a photodissociation region. To make this conclusion more quantitative we compare the physical parameters which determine the H_2 surface brightness—the UV intensity and the molecular gas density.

The far-UV ($912 > \lambda/\text{Å} > 1108$) field strength for BD +30°3639 is $\chi = 3.8 \times 10^4$ (in units of the interstellar field [Draine 1978]) at $\theta = 4''$, assuming a distance of 2.8 kpc, a central star luminosity and temperature of $L = 1.3 \times 10^4\ L_\odot$, and $T = 25{,}000$ K, while for NGC 7027 $\chi = 2.3 \times 10^4$ at $\theta = 6''$, assuming a distance of 880 pc, $L = 10^4\ L_\odot$ and $T = 140{,}000$ K (Masson 1989a, b; Underhill 1983; Jacoby 1988; Heap & Hintzen 1990; Kaler & Jacoby 1991).

Molecular emission from BD +30°3639 is detected in the CO(1–0) and (2–1) lines (Bachiller et al. 1991, 1992). The

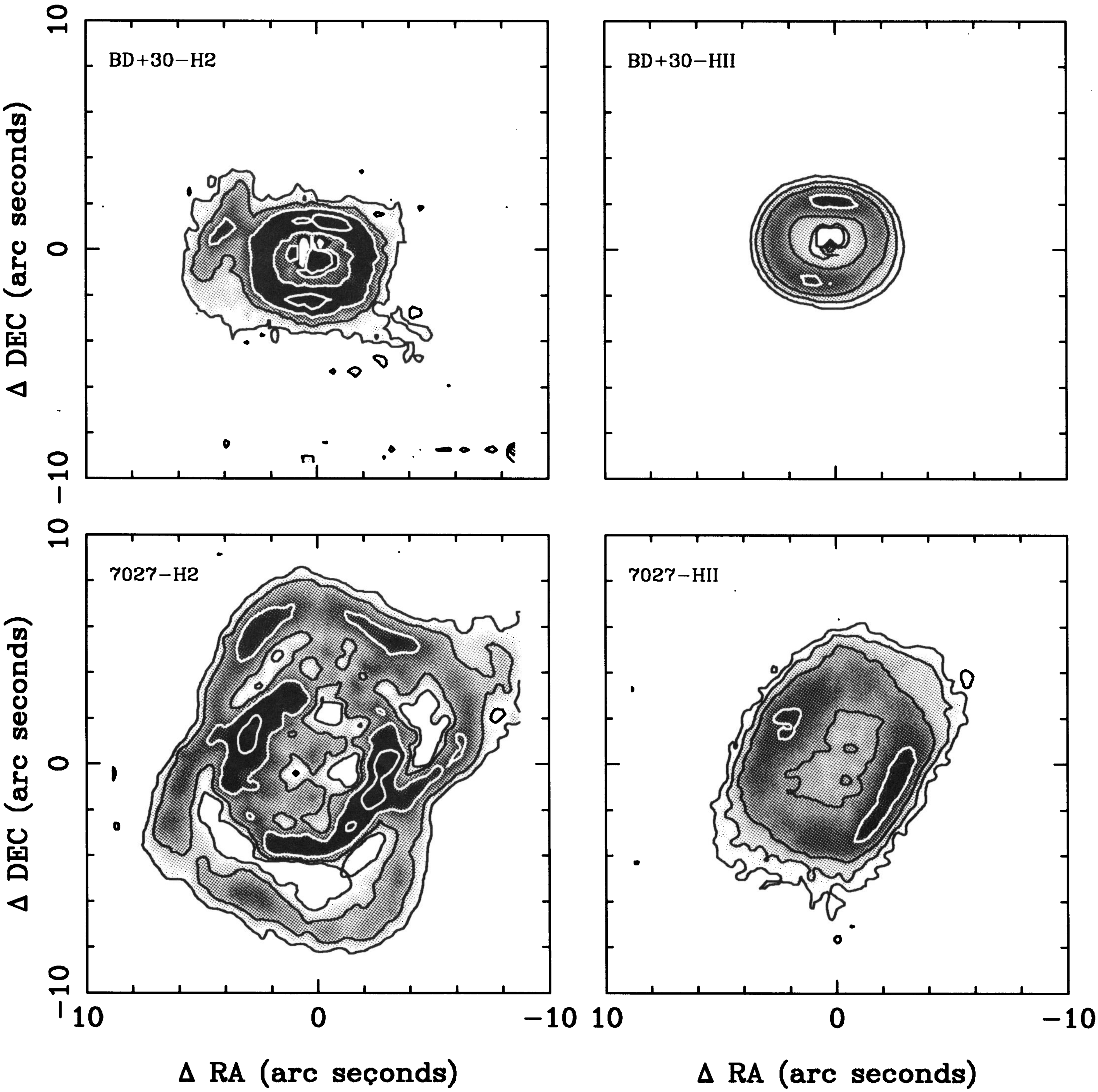

FIG. 1.—Line images of BD +30°3639 and NGC 7027 (*top* and *bottom*, respectively) showing the distribution of H_2 1–0 *S*(1) (*left*) and Brγ and Brα (*right*) emission. The 2.12 μm images include a contribution from He I 2.11 μm within the H II region. See § 3 regarding the accuracy of the continuum subtraction. The outer loops are pure H_2. Contours are logarithmic, starting at 10% of the peak intensity, and increasing by $\times 2$. In the 2.12 μm images the linear gray-scale maps black to the peak of the emission in the outer H_2 shell. In the Brγ and Brα images, black corresponds to the peak emission in the shell. The first contour for the 2.12 μm image of BD +30°3639 is 3.6×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} and for NGC 7027 2.1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}. The first contour for the Brγ image of BD +30°3639 is 2.6×10^{-3} ergs s^{-1} cm^{-2} sr^{-1} and for the Brα image of NGC 7027 4.6×10^{-2} ergs s^{-1} cm^{-2} sr^{-1}.

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absence of a strong self-absorption feature in the CO(2–1) mm line of BD +30°3639 suggests that the $J = 1$ level is thermally populated (i.e., $n \simeq n_{crit}(2\text{–}1) = 3 \times 10^4$ cm^{-3}), and therefore the density in the molecular gas adjacent to the H II region is comparable to that in NGC 7027 ($n_{H_2} \simeq 3 \times 10^4$ cm^{-3}, Jaminet et al. 1991). On the other hand the electron densities in BD +30°3639 and NGC 7027 are 2.6×10^4 and 6.9×10^4 cm^{-3}, respectively (Masson 1989b). Since the H II region is formed by ionization of the neutral envelope, the density in BD +30°3639 may be about a factor of 2 lower than NGC 7027.

If we assume that the molecular gas density in BD +30°3639 is half that in NGC 7027, then the far-UV field strength implies a UV-excited H_2 surface brightness for BD +30°3639 that is 26% lower than NGC 7027, using the theoretical scaling law of Sternberg (1988). Thus the similarity of the observed H_2 brightness and morphology in these planetary nebulae is good evidence that BD +30°3639 is also surrounded by a photodissociation region.

6. CLUMPY PHOTODISSOCIATION REGIONS AND THE ORIGIN OF FAINT OPTICAL HALOS

The H_2 and CO observations of NGC 7027 show that the molecular gas is inhomogeneous, consisting of: (1) a low-density component ($n_{H_2} \simeq 3 \times 10^4$ cm^{-3}) which is dissociated at the photodissociation front (the outer H_2 loops); (2) dense knots ($n_{H_2} \gtrsim 10^6$ cm^{-3}) that survive the passage of the photodissociation front and are eventually engulfed by the H II region (the inner ring of H_2 knots adjacent to the H II region) (Graham et al. 1993).

There is substantial evidence that the molecular gas in planetary nebulae is clumpy. For example, many planetary nebulae contain small optical condensations within the ionized gas that are bright in [O I] emission. Dyson et al. (1989) have argued that these condensations are cold dense clumps that have survived from the earliest phases of mass loss. In NGC 2440 the condensations are detected in H_2 emission and are therefore molecular (Reay, Walton, & Atherton 1988). CO mapping of evolved planetary nebulae, such as NGC 7293 (the Helix), shows that the molecular gas is fragmented into knots or filaments (Forveille & Huggins 1991). In fact unless the molecular gas is clumpy—so that it can survive in molecular form in a strong ultraviolet radiation field—it is very difficult to explain the association of H_2 and CO emission with ionized gas in evolved planetaries.

The interclump molecular gas may be related to some of the faint optical halos that are being detected in increasing numbers around planetary nebulae, and are apparently common (e.g., Balick et al. 1992). Consider the evolution of NGC 7027. Ultimately, the photodissociation front will reach the edge of the molecular envelope. This will leave the ionized core of the planetary nebula embedded in an extended halo consisting of partially ionized gas and dense molecular knots. The molecular envelope of NGC 7027 currently extends to a radius of at least 0.15 pc (Bieging et al. 1991). When NGC 7027 reaches an age of $\simeq 10^4$ yr the envelope will extend to twice this distance, if the envelope continues to expand at 14 km s^{-1} (Graham et al. 1993). The typical radii of faint optical planetary nebula halos are $\simeq$0.3 pc, and therefore, it seems likely that they are formed from the similarly sized photodissociated remnants of the molecular envelopes. Optical spectroscopy of NGC 6543 and NGC 6826 shows that the halos of these planetaries are photoionized (Middlemass, Clegg, & Walsh 1989; Manchado & Pottasch 1989). In the case of NGC 6543 the central nebula may just have become thin enough to permit ionization of the halo (Manchado & Pottach 1989). Therefore, objects at evolutionary stages between NGC 7027 or BD +30°3639 and NGC 6543 may have predominantly atomic outer envelopes which may be detectable only in tracers such at [O I] 63 μm. It is interesting that although many planetary nebulae have faint shells and halos extending beyond the high surface brightness core, BD +30°3639 and NGC 7027 do not. Perhaps this is related to the fact that the photodissociation front has not reached the edge of the molecular envelope of these planetary nebulae. (NGC 7027 has an Hα halo, but this is a reflection nebula [Atherton et al. 1979]).

7. CONCLUSIONS

BD +30°3639 and NGC 7027 have similar H_2 1–0 $S(1)$ morphology, indicating the presence of a molecular envelope with a size almost twice that of the H II region. The emission in both cases is consistent with UV excited emission from a photodissociation region. We stress the clumpy nature of the molecular envelope, and identify dense knots, which have sufficient column density to survive the passage of the photodissociation front, with cold neutral condensations responsible for bright [O I] and H_2 emission in old planetary nebulae. The faint optical halos of planetaries may be formed from the dilute neutral gas after it has passed through a photodissociation front.

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