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DETECTION OF MOLECULAR HYDROGEN EMISSION FROM FIVE PLANETARY NEBULAE

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ABSTRACT

The $v = 1 \rightarrow 0\,S(1)$ line of molecular hydrogen has been detected in five planetary nebulae. They are the Ring Nebula (M57, NGC 6720), BD+30°3639, Hb 12, CRL 618, and CRL 2688. A region in the northeast of the Ring Nebula has been mapped in both the $v = 1 \rightarrow 0\,S(1)$ molecular hydrogen line and the Brackett γ line of atomic hydrogen. The H_2 emission is not spatially correlated with the Bγ, but is correlated with the [O I] emission as determined from interference filter photographs.

Subject headings: interstellar: molecules — nebulae: planetary

I. INTRODUCTION

Emission from molecular hydrogen was first discovered in the Orion Nebula by Gautier *et al.*. (1976) and subsequently in NGC 7027 by Treffers *et al.* (1976). We have searched for the $v = 1 \rightarrow 0\,S(1)$ line of H_2 in nine planetary nebulae and their supposed progenitors (Zuckerman *et al.* 1976; Humphreys, Warner, and Gallagher 1976); positive detections were achieved in five of these, namely, the Ring Nebula (M57, NGC 6720), BD+30°3639, Hb 12 (Perek and Kohoutek 1967, No. 111 − 2°1), CRL 618 (Westbrook *et al.* 1975), and CRL 2688 (Ney *et al.* 1975; Price and Walker 1976).

All the objects with detectable H_2 emission are known to emit the λλ6300 or 6363 lines of [O I]. These lines are excited in transition zones between neutral and ionized hydrogen, and can indicate the presence of high-density neutral clumps within the ionized region (Capriotti, Cromwell, and Williams 1971; Van Blerkom and Arny 1972; Capriotti 1973; Goad 1975; Cohen and Kuhi 1977). In the case of the Ring Nebula, it is shown that the molecular hydrogen emission is spatially correlated with the [O I]. In this *Letter*, we present the observational results and only a brief discussion. More detailed analysis will be given in a later paper (Beckwith *et al.* 1978*a*).

II. OBSERVATIONS

The observations reported in this *Letter* were made on the 2.5 m Hooker telescope and the 0.6 m telescope on Mount Wilson during 1977 August. Two spectrometers were used: a grating spectrometer with 17 Å (3.8 cm^{-1}) resolution, and a circular variable filter wheel (CVF) with resolution $\Delta\lambda/\lambda = 0.014$. The grating spectrometer system and observing procedure are described in detail by Beckwith *et al.* (1978*b*); for the present observations, a circular aperture 10″ in diameter with a 60″ beam spacing for sky subtraction was used. No air-mass correction has been applied to data taken with this spectrometer. The CVF system is described in detail by Neugebauer *et al.* (1976); for the present observations a 20″ × 10″ ($\alpha \times \delta$) aperture was used with a 90″ beam spacing for sky subtraction. The air-mass correction given by Neugebauer *et al.* (1976) has been applied to data taken with the CVF.

Flux calibration was achieved by observing α Lyr, α Cyg, and 4 Lac, whose 2.2 μm magnitudes are 0.00, 0.90, and 4.25, respectively. Each standard is assumed to have a Rayleigh-Jeans continuum in the 2 μm atmospheric window.

The map of the northeast quadrant of the Ring Nebula was made with the CVF by sampling at points separated by 20″ in right ascension and 10″ in declination. The map covers a region 80″ in right ascension by 50″ in declination and is shown in Figure 1. At each location, four wavelengths were measured: 2.122 μm [$v = 1 \rightarrow 0\,S(1)$], 2.166 μm (B$\gamma$), 2.081 μm, and 2.209 μm (continuum). There could be some contamination of the 2.081 μm point by the 2.06 μm line of He I; its effect has been ignored. In addition to the map, a declination scan over the northern part of the ring was made by sampling every 5″ along a line 5″ west of the central star of the nebula. In both the map and the scan, the relative spatial uncertainty between the Bγ and H_2 measurements is no more than 2″.

A complete CVF spectrum of the brightest point in the Ring Nebula was obtained on the 0.6 m telescope on Mount Wilson. A similar spectrum of CRL 2688 was obtained on the 2.5 m Hooker telescope and is shown in Figure 4.

III. RESULTS

Table 1 lists the strengths of the $v = 1 \rightarrow 0\,S(1)$ line of H_2 and the Bγ line for the five nebulae in which H_2 emission was detected, and lists the (3 σ_m) upper limits to the $S(1)$ line strengths for the four nebulae not detected in molecular hydrogen. The identification as molecular hydrogen emission was confirmed by complete CVF spectra of CRL 2688 and the brightest point in the Ring Nebula. Both spectra clearly show the $v = 1 \rightarrow 0\,S(1)$ and $S(0)$ lines and the spectrally unresolved Q-branch lines (see Fig. 4).

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TABLE 1

MEASUREMENTS OF PLANETARY NEBULAE

Object	H_2 (2.122 μm) $v=1\rightarrow0\,S(1)$ Line $\pm1\,\sigma_m$ (10^{-13} ergs s^{-1} cm^{-2})	H I (2.166 μm) Bγ Line $\pm1\,\sigma_m$ (10^{-13} ergs s^{-1} cm^{-2})	Notes
NGC 6720.......	6.8±0.4	2.1±0.3	2, 3
BD+30°3639....	3.5±0.9	58±6	1
Hb 12...........	3.0±0.5	27±4	1
CRL 618........	4.8±0.8	<4	1, 5
CRL 2688.......	5±2	2±2	2, 4
NGC 6572.......	<2.6	105±10	5
IC 4997.........	<2.6	13±2	5
NGC 6790.......	<2	12±2	5
V1016 Cyg......	<3.3	...	5

NOTES.—(1) Measurement made with grating spectrometer; (2) measurement made with CVF system; (3) brightest point in a 10″ × 20″ aperture; (4) large error results from uncertain continuum; (5) upper limits are 3 σ_m.

a) The Ring Nebula

Figure 1 shows surface-brightness maps of H_2 and B γ emission superposed on a red photograph of the nebula. The surface brightnesses of both species of emission, like the optical radiation, are in the shape of a ring. The striking difference between the Bγ and H_2 maps is that the molecular emission lies outside the atomic emission. This result is emphasized in Figure 2*a*, which shows the declination scan along the line 5″ west of the central star. The peak brightness of the molecular hydrogen lies approximately 5″ outside the peak brightness of the atomic hydrogen.

For comparison, Figure 2*b* shows corresponding scans in the light of Hβ (λ4861) and [O I] (λ6300); these scans have been synthesized from the data of Goad (1975) to have the same spatial resolution as the infrared scans of Figure 2*a*. For the purposes of presentation, the peak of the Hβ scan has been normalized to the peak intensity of Bγ, and the [O I] to the intensity of $S(1)$. There is extremely close correspondence in the distribution of surface brightness between the Hβ and Bγ, and between the [O I] and molecular hydrogen emission. This correlation also holds for the rest of the region mapped.

b) BD+30°3639, Hb 12, CRL 618

Figure 3 shows the measured profile of the $v = 1 \rightarrow 0\,S(1)$ line in the objects BD+30°3639, Hb 12, and CRL 618. The continuum level was established from the extreme points of each spectrum [i.e., outside the expected $S(1)$ profile]; in each case this continuum level is consistent with a 2.2 μm broad-band measurement. Although the signal-to-noise ratio is rather low, there is some indication that the $S(1)$ line in CRL 618 is blue-shifted by 4 Å, corresponding to $v_{LSR} \sim -35$ km s^{-1}. This is consistent to within the measurement uncertainties with the velocity $v_{LSR} \sim -50$ km s^{-1} found by Westbrook *et al.* (1975).

c) CRL 2688

Figure 4 shows the CVF spectrum of CRL 2688. The molecular hydrogen emission lines $v = 1 \rightarrow S(1)$ and $S(0)$ and the Q-branch are clearly seen in this spectrum. At the resolution of the CVF it is difficult to fit a continuum level to the observations. The Bγ line is not positively detected; this emphasizes that the strength of molecular hydrogen emission is not correlated with the strength of Bγ emission.

IV. DISCUSSION

The principal conclusion of this *Letter* is that H_2 molecules are found in planetary nebulae. The detectable objects span a wide range in age and morphology: CRL 618 and CRL 2688 are thought to be progenitors of planetary nebulae (Westbrook *et al.* 1976; Ney *et al.* 1976; but see also Humphreys, Warner, and Gallagher 1976); NGC 7027, BD+30°3639, and Hb 12 are young, high-density ($N_e \geq 10^4$ cm^{-3}) nebulae (Kaler 1970; O'Dell 1963); and NGC 6720 is an old nebula in which the electron density in the diffuse regions is only ~600 cm^{-3} (Aller, Epps, and Czyzak 1976). The difference in age between these objects is at least a few thousand years. The detection of H_2 in CRL 618 and CRL 2688 may provide support for the suggestion that these objects are, in fact, destined to become classical planetary nebulae.

The second conclusion of this *Letter* is that the H_2 and [O I] emission line strengths are spatially correlated in NGC 6720. The nature of this correlation cannot be derived in detail from the present data, but the overall similarity of the declination scans of H_2 and [O I] in Figure 2 shows that it is likely that the molecules are intimately associated with the [O I] clumps visible on interference filter photographs (Capriotti, Cromwell, and Williams 1971; Goad 1975). A comparison of the line ratios $v = 1 \rightarrow 0\,S(1)$/B γ and [O I]/Hβ from object to object tends to show a similar correlation. In view of the fact that the [O I] emission must arise in the transition zones (ionized to neutral) or in the shadows of dense filaments optically thick to the Lyman-continuum radiation (Van Blerkom and Arny 1972), it is plausible, as predicted by Capriotti (1973), that the H_2 molecules reside inside the clumps, protected from the dissociating radiation by dust grains.

NGC 7027, BD+30°3639, and the Ring Nebula have been searched for CO emission (Mufson, Lyon, and Marionni 1975). The data show that a molecular cloud surrounds the optical nebula NGC 7027. In BD+30°3639 and the Ring Nebula, CO was not detected at a level more than an order of magnitude less than that from NGC 7027. The present H_2 results are very different: the strength of the H_2 $v = 1 \rightarrow 0\,S(1)$ line in NGC 7027 is only 3 times brighter than that in BD+30°3639.

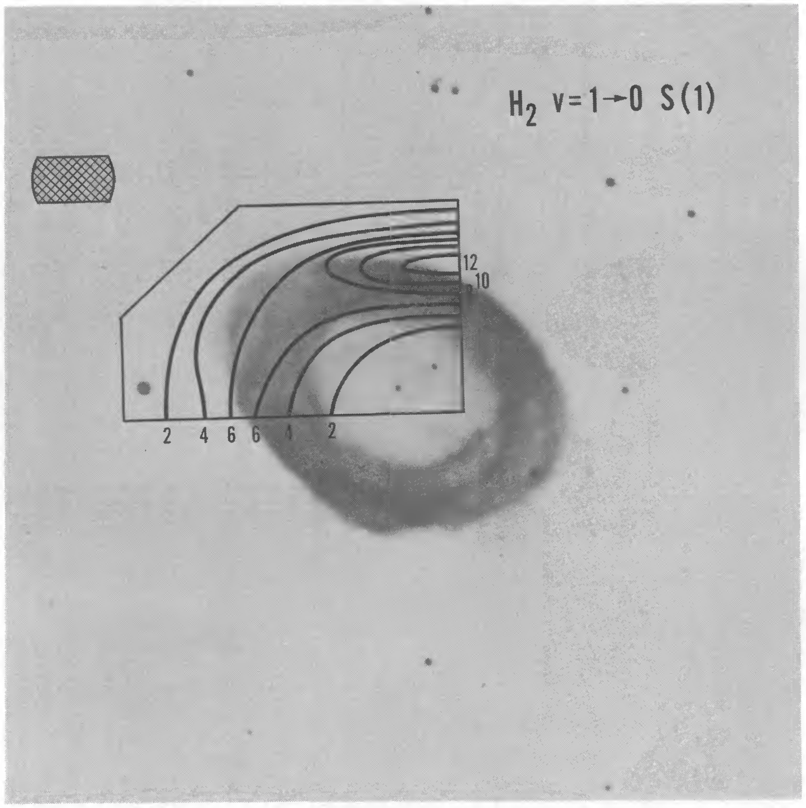

FIG. 1a

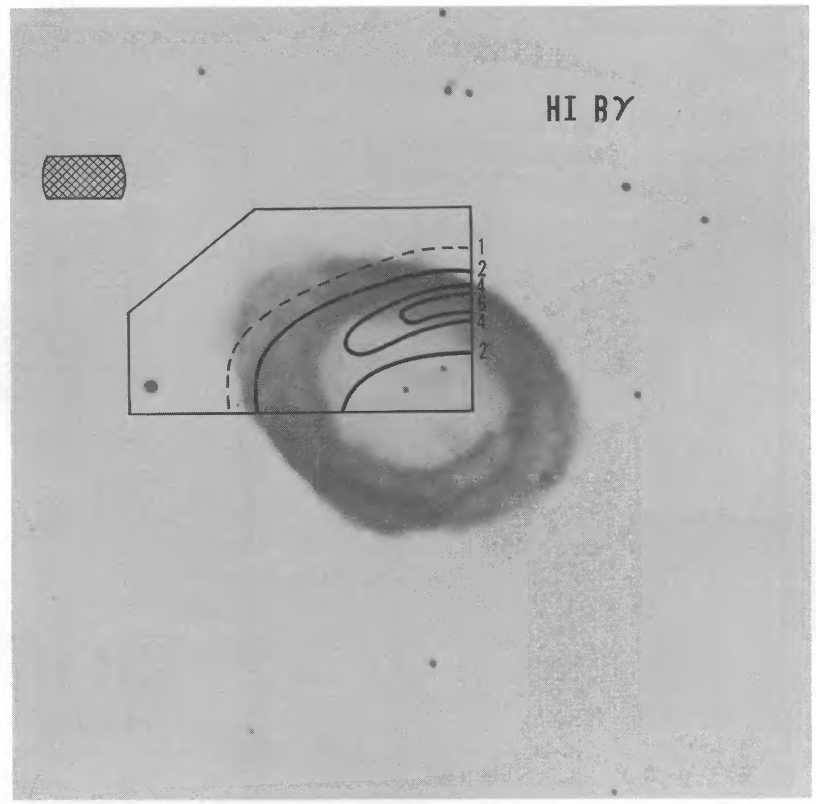

FIG. 1b

FIG. 1.—Partial maps of H_2 surface brightness (a) and Bγ surface brightness (b) overlayed on a picture of the Ring Nebula taken on the 200 inch (5.08 m) Hale telescope through a red filter. The beam size is shown by the crosshatched area on each map. Northeast is in the upper left corner. Labeled contour levels are in units of 10^{-5} ergs s^{-1} cm^{-2} sr^{-1} for both maps. The distance between the central star and the bright star directly east of the nebula is 60″.

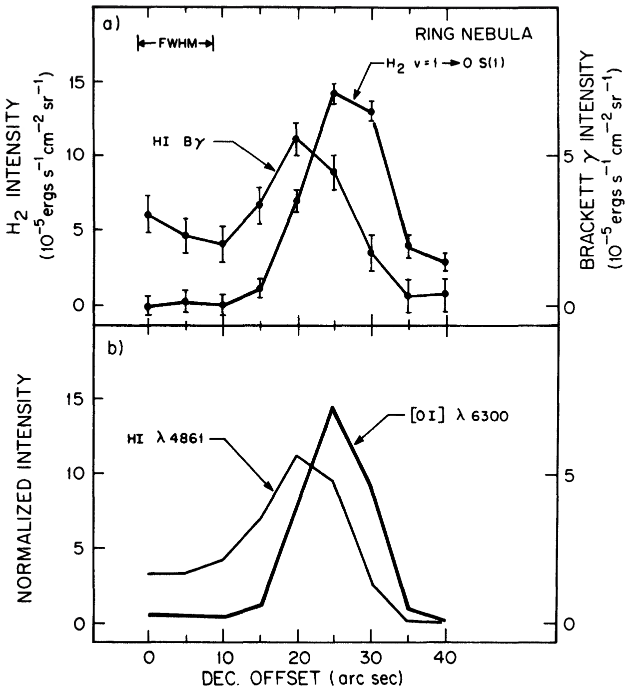

FIG. 2.—Scans taken along a line 5″ west of the central star with the abscissa indicating the declination offset north of the central star. The resolution was 10″, as indicated by FWHM. Lines are drawn between the points as an aid to the eye. Plot of Hβ and [O I] λ6300 surface brightness derived from the data of Goad (1975). The Hβ profile is normalized so that the peak brightness is the same height as the peak brightness in Bγ. Similarly, the [O I] peak is normalized to the H_2 peak. The spatial resolution of Goad's original work has been degraded here to match the spatial resolution of the Bγ and H_2 observations.

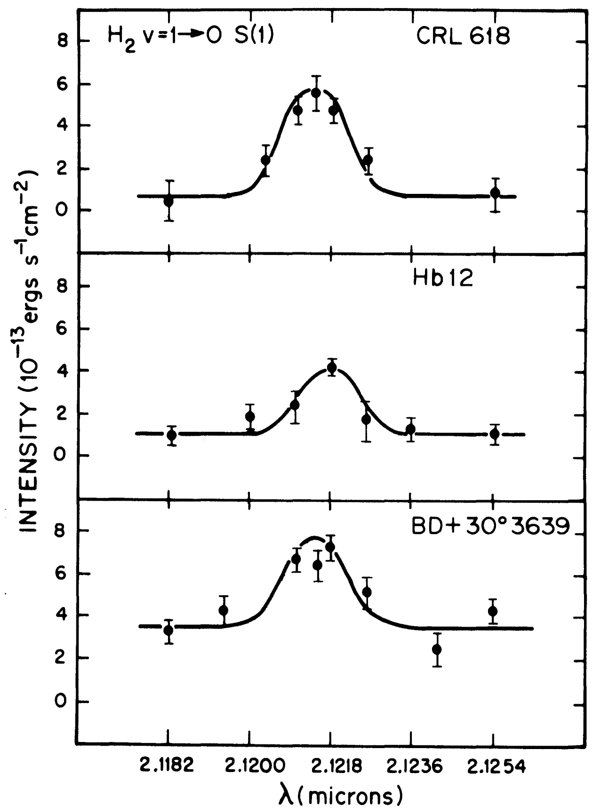

FIG. 3.—The measurements of BD+30°3639, Hb 12, and CRL 618 made with the grating spectrometer system. The intensity and wavelength scales are the same for all plots. The continuum flux level was determined by averaging the points that are 18 Å or more from the line center. In each case the measured instrumental profile, appropriately normalized and centered, has been drawn through the data to aid the eye.

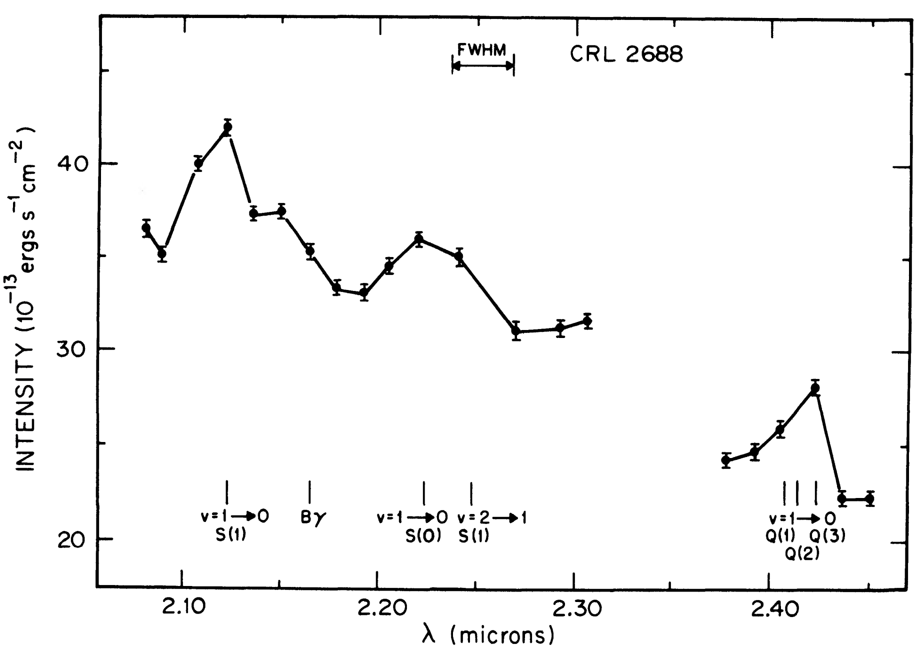

FIG. 4.—The spectrum of CRL 2688 taken with the CVF. The zero level has been suppressed. The wavelengths of Bγ and six molecular hydrogen lines are marked for comparison, and the points are connected to aid the eye wherever the sampling was complete.

It thus appears that a molecular cloud is not necessary for H_2 emission. This supports the hypothesis that the molecular hydrogen exists inside the neutral clumps.

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