DISCOVERY OF Lyα-PUMPED MOLECULAR HYDROGEN EMISSION IN THE PLANETARY NEBULAE NGC 6853 AND NGC 3132

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ABSTRACT

We report the first observation of Lyα pumped molecular hydrogen emission lines in planetary nebulae. The H₂ emission observed in the ultraviolet spectra of NGC 6853 and NGC 3132 can be explained by excitation of vibrationally hot H₂ by Lyα photons. Constraints are placed on the nebular Lyα emission profile, as well as the molecular hydrogen temperature, column density, and turbulent motion. These parameters are similar for the two nebulae, pointing to similar physical conditions in these objects. The rovibrational cascade following Lyα pumping is predicted to have low surface brightness signatures in the visible and near-infrared.

Subject headings: ISM: molecules — planetary nebulae: individual (NGC 3132, NGC 6853) — ultraviolet: ISM

Online material: color figure

1. INTRODUCTION

Molecular hydrogen emission is often seen in the infrared (IR) observations of photodissociation regions within planetary nebulae (PNe; Zuckerman & Gatley 1988; Kastner et al. 1996). Continuum pumped ultraviolet (UV) fluorescence, as observed in reflection nebulae and star-forming regions (Witt et al. 1989; France & McCandliss 2005), has not been detected in PNe. The observed IR quadrupole emission originates in elevated rovibrational levels of the ground electronic state \( X^1\Sigma^+_g \). The distribution of molecules in these levels is characteristic of either shock heating (Zuckerman & Gatley 1988) or radiative cascade from excited electronic states (Hayashi et al. 1985; Gatley et al. 1987). UV fluorescence can result in the dissociation of the molecule 10%–15% of the time (Stecher & Williams 1967) or a nonthermal population in the excited rovibrational levels of \( X^1\Sigma^+_g \). Shocks, with specific temperatures of \( \sim 2000 \) K, can thermally populate higher rovibrational states, resulting in IR transitions without the far-UV cascade (Takami et al. 2000). Detection of the UV fluorescence in conjunction with models of the IR to UV scaling of H₂ emission can constrain the contribution of each mechanism to the IR flux.

The line-pumped H₂ UV fluorescence described in this paper is consistent with measured IR line ratios and gas temperatures that favor the shock excitation scenario (Zuckerman & Gatley 1988; Storey 1984). As shown in § 4.1.5, this type of UV emission, unlike continuum-pumped fluorescence, has little effect on the observed IR spectrum. Weak specific features are expected in the optical.

At typical diffuse interstellar medium (ISM) temperatures below 100 K (Rachford et al. 2002), only H₂ molecules in the \( v'' = 0 \) level of \( X^1\Sigma^+_g \) make a significant contribution to the UV fluorescence. These molecules are excited by 912 Å to 1110 Å radiation into vibrational and rotational levels of higher electronic states (mainly \( B^1\Sigma^+_u \) and \( C^1\Pi_u \); Black & van Dishoeck 1987). As the temperature increases, higher rovibrational levels of \( X^1\Sigma^+_g \) become populated, and the threshold for fluorescent pumping moves to progressively larger wavelengths. Due to the long lifetime of the \( X^1\Sigma^+_g \) levels, the molecules can be further pumped to \( B^1\Sigma^+_u \) or \( C^1\Pi_u \) by a sufficiently strong radiation field before they have time to radiate. This mechanism is predicted to be important for nebular gas densities in the range \( 10^4 \) cm\(^{-3} \) \( \leq n \leq 10^6 \) cm\(^{-3} \) and a radiation field (in units of the interstellar average) of \( 10^3 \) \( \leq G_0 \leq 10^4 \) (Sternberg 1989).

We have found that in both NGC 6853 (M27, The Dumbbell Nebula) and NGC 3132 H₂ UV fluorescence is dominated by lines pumped by nebular Lyα from the excited \( v'' = 2 \) level of \( X^1\Sigma^+_g \) to the \( B^1\Sigma^+_u \) states. Molecular hydrogen resonance fluorescence with Lyα has been previously recognized as an important contributor to the UV flux in collisional environments of photodissociation regions. This effect was first pointed out by Shull (1978) and discussed further by Black & van Dishoeck (1987). Lyα pumping was predicted to be significant mainly for T Tauri stars and Herbig-Haro objects, as has been subsequently observed (Brown et al. 1981; Schwartz 1983; Raymond et al. 1997; Herczeg et al. 2004). Other environments in which Lyα pumping was detected include solar system objects (Wolven et al. 1997; Jordan et al. 1977) and accreting systems (Gizis et al. 2005; Wood et al. 2002). In this paper we present for the first time evidence for resonant excitation by Lyα of the \( B^1\Sigma^+_u \) level of \( \lambda_\text{Lyα} = 1215.73 \) Å in planetary hydrogen lines in PNe. The observed resonances and line ratios are a valuable diagnostic tool for molecular gas temperature, Lyα line shape, and Doppler shift relative to the H₂ absorber.

The first object, NGC 6853, is a 12,700-year-old PN (O’Dell et al. 2002) at a distance of 417 ± 50 pc (Benedict et al. 2003). Its central star has a temperature 108,600 ± 6800 K (Benedict et al. 2003). The distance to NGC 3132 is not well known, varying from 1.63 kpc (Torres-Peimbert & Peimbert 1977) to 0.51 kpc (Pottasch 1996), while the temperature of the ionizing star is estimated at 110,000 K (Pottasch 1996). The extinction, as measured by \( E(B-V) \) in this case, is of the order of 0.1 for the central star in both cases (Benedict et al. 2003; Pottasch 1996).

However, S. R. McCandliss et al. (2006, in preparation) argue that in the case of NGC 6853 the extinction is negligible. In both cases, the detected Lyα pumped H₂ fluorescence requires a temperature of \( \sim 2000 \) K and column densities of \( \sim 10^{18} \) cm\(^{-2} \), as well as a Lyα profile of \( \sim 0.4 \) Å width, with a deep self-reversal. These parameters satisfy both short- and long-wavelength constraints, pointing to similar conditions of the molecular gas in the two nebulae.

A description of the observations and data is found in § 2. Data analysis follows in § 3, and a discussion of the results is in § 4.

2. OBSERVATIONS

Four nebular observations of NGC 6853 were made by the Far Ultraviolet Spectroscopic Explorer (FUSE) on 2004 May 26
Fig. 1.—Optical image of NGC 6853 obtained during the commissioning of the FORS1 instrument on the Very Large Telescope 8.2 m. This three-color image was made from a composite of B, [O iii], and H$\alpha$ filters. **FUSE** LWRS aperture overlays are imposed showing the location of the four nebular pointings 1–4 from left to right. The optical image was obtained from the European Southern Observatory. [See the electronic edition of the Journal for a color version of this figure.]

using the low-resolution (LWRS) aperture ($30'' \times 30''$; Fig. 1). Spectra were obtained in the 905–1187 Å bandpass at a filled aperture resolution of $\sim 0.33$ Å. A description of the **FUSE** satellite can be found in Moos et al. (2000), and on-orbit performance characteristics are described by Sahnow et al. (2000). The data were acquired as part of the E120 guest observing program. The pointings extend along the bright bar structure of the nebula, from the northeast to the southwest (Fig. 1). Data for all four pointings were obtained in “time-tagged” (TTAG) mode and processed using the CalFUSE pipeline, version 2.4.2. The average exposure time was 3374 s. The log of the observations of NGC 6853 is presented in Table 1.

We obtained optical spectra of NGC 6853 on 1999 June 9 using the Double Imaging Spectrograph (DIS) on the Apache Point Observatory (APO) 3.5 m telescope. The observations were taken with the low-resolution gratings, centered at 8000 and 4224 Å with a dispersion of 7.0 Å pixel$^{-1}$ in the red side and 6.1 Å pixel$^{-1}$ in the blue side, and a resolution of roughly 2 pixels. The $300'' \times 09''$ slit was centered at (R.A. = 19°59'36"20, decl. = 22°43'01"00) and oriented along the bright bar. Three slit positions (about 277 total width) were averaged during the 900 s integration. The observed mean H$\alpha$ brightness along the slit was about $4.68 \times 10^{-3}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$, or 19,416 R [conversion factor 632 Å$_{\text{rest}}$ Å].

NGC 3132 was observed by the Hopkins Ultraviolet Telescope (HUT) on board Astro-2 for 946 s during orbital night on 1995 March 14. This spectrum, downloaded from the Multimission Archive at the Space Telescope Science Institute (MAST), was acquired through the $10'' \times 56''$ slit, enclosing a large region of the 28$''$ nebula, at an offset from the central stars. The exact slit coordinates are uncertain. The resolution of the HUT spectrum is roughly 3 Å. A description of the HUT instrument and data reduction can be found in Kruij et al. (1995). The signature of H$\alpha$ emission is present in the **FUSE** spectrum of NGC 3132 (D1200401), but at a considerably lower signal-to-noise ratio. We chose to analyze the HUT spectrum because it allows us to extend our study to longer wavelengths.

3. DATA ANALYSIS

3.1. NGC 6853

The **FUSE** spectra of NGC 6853 position 3 are presented in Figures 2 and 3. The emission from the nebula is dominated by He II, C II, C III, and molecular hydrogen lines. The strongest lines observed in all four pointings are summarized in Tables 2–5. The lines denoted by letters A–D are unidentified. Feature A is possibly nebular O III (\$\lambda$662.425) at a slight velocity offset. The strengths of the lines in the spectrum change with the pointing. The highly ionized species dominate in the central regions and decline toward the outer shell. Molecular hydrogen lines are present in all four pointings and are strongest in the third pointing, which coincides with the brightest optical feature.

We explored the possibility that line pumped H$_2$ fluorescence is responsible for some of the unidentified lines we observe, computing models with a variety of nebular emission lines as the excitation source. Atomic emission lines of H II, Ly$\beta$, Ly$\gamma$, He II $\lambda$$\lambda$1215, 1085, 1025, 972, and 959; C II $\lambda$$\lambda$1334/35 and $\lambda$$\lambda$1036/37; the C III $\lambda$$\lambda$1175 multiplet and C IV $\lambda$$\lambda$1977; N I $\lambda$1200; the N II $\lambda$1085 multiplet; the N III $\lambda$990 multiplet; and the O VI resonance doublet $\lambda$$\lambda$1032/38 were all considered as possible H$_2$ excitation mechanisms. None of the strongest predicted fluorescent emission lines are observed.

The strongest H$_2$ lines observed are excited by the $B-X (1-2) P(5)$ transition at 1216.07 Å in the red wing of Ly$\alpha$. Their wavelengths and branching ratios are listed in Table 6. These transitions are sensitive to the Ly$\alpha$ line width and Doppler shift. Although the closest resonance is $B-X (1-2) R(6)$ at 1215.73 Å, Lyman system fluorescence from $v' = 1, J' = 7$ is far weaker than expected. This can be achieved with a deep self-reversal of the Ly$\alpha$ profile combined with a blueshifting of the molecular hydrogen lines with respect to the systemic Ly$\alpha$ emission. The blueshift is necessary to restore to some extent the intensities of the lines pumped by the $B-X (1-2) R(6)$ resonance, which otherwise would fall in the center of the absorption trough (Fig. 4).

| Instrument          | Program | Date       | R.A.   | Decl.   | Exposure Time (s) |
|---------------------|---------|------------|--------|---------|-------------------|
| **FUSE** LWRS........| E12001  | 2004 May 26| 19 59 44.96| +22 44 50.1| 4176.0            |
| **FUSE** LWRS........| E12002  | 2004 May 26| 19 59 38.93| +22 44 04.0| 3071.0            |
| **FUSE** LWRS........| E12003  | 2004 May 26| 19 59 32.35| +22 42 35.1| 2778.0            |
| **FUSE** LWRS........| E12004  | 2004 May 26| 19 59 27.27| +22 42 10.3| 3470.0            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
NGC 6853, as well as NGC 3132, was modeled using a fluorescent H$_2$ emission code similar to the one described in France et al. (2005). The exciting radiation field was assumed to be a Gaussian Ly$\alpha$/C$\text{ii}$ emission line, with a FWHM of 0.48. In order to mimic self-reversal, absorption by neutral hydrogen with a column density of 1.10$^{14}$ cm$^{-2}$ was used to modify the exciting Ly$\alpha$/C$\text{ii}$ profile (Fig. 4). As the nebular Ly$\alpha$ line cannot be measured directly due to the opacity of the ISM and contamination from geocoronal Ly$\alpha$, a total brightness was chosen as two-thirds of the H$\alpha$/C$\text{ii}$ brightness of 19,416.0 R measured using the DIS at APO (see § 2). According to the selection rules, two-thirds of the time the H$\alpha$ transitions will result in an atom in the 2$p$ state, which can then radiate a Ly$\alpha$ photon during the 2$p$–1$s$ transition. The other one-third of the time, the hydrogen atom will be left in the 2$s$ state, unable to emit a Ly$\alpha$ photon since a direct transition from this state to 1$s$ is forbidden in the dipole approximation (Spitzer 1978). The total Ly$\alpha$ brightness could be higher than derived from H$\alpha$ measurements, due to H$_2$ dissociation mechanisms that produce H 1 in the 2$p$ state (Glass-Maujean 1986). The continuum flux from the central star of NGC 6853 has not been included because continuum pumped emission lines are not detected in the H$\alpha$ brightness of 19,416.0 R measured using the DIS at APO (see § 2). According to the selection rules, two-thirds of the time the H$\alpha$ transitions will result in an atom in the 2$p$ state, which can then radiate a Ly$\alpha$ photon during the 2$p$–1$s$ transition. The other one-third of the time, the hydrogen atom will be left in the 2$s$ state, unable to emit a Ly$\alpha$ photon since a direct transition from this state to 1$s$ is forbidden in the dipole approximation (Spitzer 1978). The total Ly$\alpha$ brightness could be higher than derived from H$\alpha$ measurements, due to H$_2$ dissociation mechanisms that produce H 1 in the 2$p$ state (Glass-Maujean 1986). The continuum flux from the central star of NGC 6853 has not been included because continuum pumped emission lines are not detected in the H$\alpha$ brightness of 19,416.0 R measured using the DIS at APO (see § 2). According to the selection rules, two-thirds of the time the H$\alpha$ transitions will result in an atom in the 2$p$ state, which can then radiate a Ly$\alpha$ photon during the 2$p$–1$s$ transition. The other one-third of the time, the hydrogen atom will be left in the 2$s$ state, unable to emit a Ly$\alpha$ photon since a direct transition from this state to 1$s$ is forbidden in the dipole approximation (Spitzer 1978). The total Ly$\alpha$ brightness could be higher than derived from H$\alpha$ measurements, due to H$_2$ dissociation mechanisms that produce H 1 in the 2$p$ state (Glass-Maujean 1986). The continuum flux from the central star of NGC 6853 has not been included because continuum pumped emission lines are not detected in the

### Table 2

| Line ID | $\lambda_{\text{obs}}$ (Å) | FWHM (Å) | Brightness ($10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$) |
|---------|-----------------|----------|----------------------------------|
| C ii    | 946.01          | 0.56     | 1.83 ± 0.29                     |
| He ii   | 958.52          | 0.53     | 0.35 ± 0.28                     |
| N iii + He ii | 991.52 | 0.21     | 1.91 ± 0.39                     |
| C ii    | 1036.88         | 0.33     | 1.37 ± 0.22                     |
| N ii + He ii | 1085.50 | 0.34     | 25.75 ± 1.03                    |
| C ii    | 1141.53         | 0.26     | 0.36 ± 0.13                     |
| H$_2$(1–1) R(3) | 1148.59 | 0.43     | 0.40 ± 0.14                     |
| H$_2$(1–1) P(5) + R(6) | 1161.76 | 0.32     | 0.71 ± 0.16                     |
| C iii   | 1175.53         | 0.48     | 1.97 ± 0.23                     |
| H$_2$(1–1) P(8) | 1183.06 | 0.21     | 0.92 ± 0.32                     |

**Note:** The C iii line at 977.03 Å is not listed due to contamination from scattered solar light in the SiC channels.
nebular spectra. The likely explanation for the absence of continuum pumped fluorescence resides in the dominance of Ly$\alpha$ photons over the 912–1110 Å stellar continuum as well as the small covering factor involved in the absorption of continuum radiation, as is discussed in § 4.

The model parameters summarized in Table 7 were adjusted to reproduce the 1115–1187 Å line strengths observed in the LiF 1B channel. The LiF 2A channel (Fig. 2) shows a 20% decrease in the (1–1) $R(3)$ brightness, which we attribute to calibration offsets. The molecular hydrogen temperature of 2040 K was derived from absorption spectra (S. R. McCandlish et al. 2006, in preparation). The H$_2$ absorption is blueshifted with respect to the Ly$\alpha$ profile by about $-25$ km s$^{-1}$, a value supported by recent studies of NGC 6853 (McCandlish et al.), assuming Ly$\alpha$ at the systemic velocity. The chosen total Ly$\alpha$ brightness constrains the molecular hydrogen column density of $6 \times 10^{18}$ cm$^{-2}$. An H$_2$ column density of a few times $10^{16}$ cm$^{-2}$, as inferred from absorption spectra (McCandlish et al.), would require a much higher Ly$\alpha$ brightness.

3.2. NGC 3132

In analyzing the NGC 3132 spectrum it is important to account for the background. The continuum has a very unusual shape, most likely due to the superposition of the central stars and the inhomogeneous dust distribution within the nebula. A detailed analysis of the continuum is beyond the scope of this work, but a rough baseline is needed for the model H$_2$ spectrum. We set this background by manipulating the original HUT spectrum to extract a smooth continuum curve. A broad (width $\approx 75$ Å) median filter was applied to the data at wavelengths between 1100 and 1750 Å to remove most of the nebular and geocoronal emission lines. A boxcar smooth (width $\approx 20$ Å) was then applied, leaving a background continuum spectrum. Measured brightnesses for the strongest lines are given in Table 8. The observed H$_2$ emission lines provide a long-wavelength confirmation of pumping by Ly$\alpha$ photons.

We use the NGC 6853 model as a starting point for NGC 3132, as a detailed study of the molecular structure of NGC 3132 was not available. Previous observations and models of NGC 3132 (Monteiro et al. 2000; Bässgen et al. 1990) estimate the nebular H$\alpha$ luminosity at $\sim$ a few times $10^{44}$ photons s$^{-1}$, too low to predict the observed level of H$_2$ fluorescence. This value was derived using a distance of 670 pc, which might be an underestimate. The estimated total H$\alpha$ luminosity of NGC 6853, approximated as an elliptical nebula with semimajor axes of $2.5'$ and $4'$, at a distance of 417 pc, is $8.55 \times 10^{46}$ photons s$^{-1}$. Using for the NGC 3132 $0.45 \times 0.7'$ nebula a total H$\alpha$ luminosity of $\sim 1 \times 10^{47}$ photons s$^{-1}$, closer to the value for NGC 6853, we obtain a reasonable fit with column densities of $3 \times 10^{18}$ cm$^{-2}$ for the molecular component and $2 \times 10^{16}$ cm$^{-2}$ for the atomic hydrogen. The molecular hydrogen absorption is blueshifted with respect to the nebular Ly$\alpha$ by $-30$ km s$^{-1}$, in agreement with other measurements (Monteiro et al. 2000). A summary of the parameters used is given in Table 7. The overprediction of line strengths in the 1200 $\leq \lambda \leq 1300$ Å region (Fig. 5) and shortward of 1200 Å (not shown) is caused by an incomplete removal of the combination of geocoronal Ly$\alpha$ and the (1–3) H$_2$ emission band together with opacity effects. These shorter wavelength lines connect to more populated lower vibrational levels (Table 6),
leading to self-absorption (Herczeg et al. 2004; Wood et al. 2002).

4. DISCUSSION

Although H$_2$ absorption was observed in both nebulae (S. R. McCandliss et al. 2006, in preparation; Sterling et al. 2002), continuum pumped molecular hydrogen emission was not detected. Predicted continuum pumped UV fluorescence for an H$_2$ column density of 7.9 $\times$ 10$^{16}$ cm$^{-2}$, measured from absorption spectra (McCandliss et al.), is estimated at a level of ~0.7 $\times$ 10$^{-6}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$, consistent with the noise level in Figure 2. However, the larger column density used in the Ly$\alpha$ pumping model would predict a much higher continuum fluorescence, which is not observed. One possible explanation comes from the dominance of Lyman continuum photons over the 912–1110 Å photons that contribute to continuum H$_2$ pumping. In the central H ii region of a PN, Lyman continuum photons are readily converted into Ly$\alpha$ line photons, following a series of ionizations, recombinations, and cascades. Integrating a stellar model with $T_{eff}$ = 110,000 K, log ($g$) = 6.7, and $M_*$ = 0.56 $M_\odot$ (Rauch 2003), we find that there are over 16 times more photons cm$^{-2}$ s$^{-1}$ emitted in the Lyman continuum (5–911.7 Å) than in the 912–1110 Å region. In addition, the Lyman continuum photons are concentrated into an emission line (FWHM$_{Ly\alpha}$ = 0.4 Å), compared with the far-UV stellar continuum that spans roughly 200 Å.

| Parameter | NGC 6853 | NGC 3132 |
|-----------|----------|----------|
| Excitation source | H i Ly$\alpha$ | H i Ly$\alpha$ |
| Ly$\alpha$ Doppler shift | 25 km s$^{-1}$ | 30 km s$^{-1}$ |
| Ly$\alpha$ FWHM | 0.40 Å | 0.45 Å |
| Ly$\alpha$ total intensity | 12944 R | 217523 R |
| $T(H_2)$ | 2040 K | 2040 K |
| $N(H_2)$ | 6.0 $\times$ 10$^{15}$ cm$^{-2}$ | 3.0 $\times$ 10$^{15}$ cm$^{-2}$ |
| $N(H \beta)$ | 1.0 $\times$ 10$^{15}$ cm$^{-2}$ | 2.0 $\times$ 10$^{15}$ cm$^{-2}$ |
| $b$ | 8 km s$^{-1}$ | 9 km s$^{-1}$ |
For an H\(\text{II}\) region with an electron temperature of 12,000 K (i.e., NGC 6853; Pottasch et al. 1982) the recombination efficiency for generating Ly\(\alpha\)/C\(1\) photons is roughly 67% (Spitzer 1978), which gives us \(5 \times 10^{45} \text{photons s}^{-1}\). The total Ly\(\alpha\)/C\(1\) luminosity obtained this way is still low compared to the value of \(8 \times 10^{45} \text{photons s}^{-1}\) derived from the H\(\beta\)/C\(1\) brightness. This shows that the ratio of Ly\(\alpha\) photons to 912–1110 \(\text{Å}\) continuum photons might be even higher than estimated. However, the dominance of Ly\(\alpha\) photons over the 912–1110 \(\text{Å}\) stellar continuum alone is not sufficient to compensate for the larger ground-state populations and higher oscillator strengths contributing to other Lyman and Werner transitions out of \(\nu^0 = 0\). Assuming that molecules reside in high-density globules, the covering factor involved in continuum excitation is much smaller than for the diffuse radiation field of scattered Ly\(\alpha\). If we let \(B_0\) be the surface brightness of the exciting field, the total flux absorbed by an H\(\text{II}\) clump will be \(B_0 \Omega\), where \(\Omega\) is the solid angle subtended by the absorber, as seen from the source. The redistributed brightness is then radiated into \(4\pi\), so that we can define an effective surface brightness seen by the absorber as \((B_0 \Omega)/4\pi\), where \(\Omega/4\pi\) is the covering factor. For a 10\(''\) × 10\(''\) globule at a 50\(''\) separation from the central star, the continuum covering factor is about 0.0032, while for the nebular Ly\(\alpha\) it is likely to be unity. This estimate takes into account that, while the continuum photons are coming mainly from the star, the Ly\(\alpha\) photons are produced and scattered in the nebula, so that the globules are effectively embedded in a diffuse Ly\(\alpha\) radiation field covering all \(4\pi\) sr.

The broad (98.6 km s\(^{-1}\) FWHM) Ly\(\alpha\) line required to pump the H\(\text{II}\) lines in NGC 6853 is likely to originate in the complex shell structure of the nebula. As shown by Meaburn et al. (2005), in the case of H\(\beta\) the wide profile is a result of combining the motions of the outer shell at 35 km s\(^{-1}\), the inner shell at 13 km s\(^{-1}\), and the bulk motion at less than 7 km s\(^{-1}\) in the central H\(\text{II}\) region. We infer that a similarly broad velocity structure should be present in NGC 3132 to produce a Ly\(\alpha\) of comparable width. A narrower velocity distribution would be allowed if we take into account the redistribution of the Ly\(\alpha\) photons in the line wings for large optical depths.

IR observations of NGC 6853 and NGC 3132 made to date (Storey 1984; Zuckerman & Gatley 1988) conclude that the H\(\text{II}\) spectrum is shock excited based on the ratios of the \(S(1)\) (1–0) and \(S(1)\) (2–1) lines. Moreover, this conclusion is supported by the nondetection of continuum-pumped UV fluorescence, both in these spectra and in rocket observations of the Dumbbell (McCandliss 2001). However, recent studies (Hora et al. 1999; Takami et al. 2000) have shown that in dense enough environments the ratio of the \(S(1)\) (1–0) and \(S(1)\) (2–1) lines can appear thermal, even if the IR emission is excited via UV pumping. In

| Line ID          | \(\lambda_{\text{obs}}\) (Å) | FWHM (Å) | Brightness \(\left(10^{-6} \text{ergs cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\right)\) |
|------------------|-------------------------------|----------|----------------------------------|
| H\(2\) (1–3) R(3) | 1259.19                       | 4.14     | 8.62 ± 0.48                     |
| H\(2\) (1–3) P(5) | 1273.38                       | 3.57     | 16.81 ± 0.52                    |
| H\(2\) (1–6) R(3) | 1431.73                       | 2.41     | 11.86 ± 0.53                    |
| H\(2\) (1–6) P(5) | 1446.67                       | 4.01     | 26.75 ± 0.62                    |
| H\(2\) (1–7) R(3) | 1489.85                       | 2.27     | 23.12 ± 0.64                    |
| H\(2\) (1–7) P(5) | 1505.84                       | 2.41     | 22.59 ± 0.58                    |
| H\(2\) (1–8) R(3) | 1548.16                       | 2.89     | 15.54 ± 0.64                    |
| H\(2\) (1–8) P(5) | 1563.10                       | 1.92     | 14.35 ± 0.64                    |
| H\(2\) (1–9) P(5) | 1617.69                       | 1.28     | 7.04 ± 0.75                     |

Fig. 5.—HUT spectrum of NGC 3132. The H\(\text{II}\) model added to an empirical fit to the continuum is shown in red (see text).
these cases, the study of transitions from higher energy levels becomes important in order to distinguish between the two mechanisms. The detection of H$_2$ continuum absorption toward the central star of NGC 6853 shows that continuum pumped fluorescence takes place, although at a level allowed by a nondetection in the FUSE spectra. This by itself does not rule out a partial UV continuum pumping of the IR lines. However, the thermal processes are thought to be dominant, since absorption out of vibrational levels $v > 2$ is not observed, in contrast to reflection nebulae where fluorescence is important (Meyer et al. 2001). The possibility of shock excitation in NGC 6853 and NGC 3132 is also revealed here by the high temperature required by the presence of Ly$\alpha$ pumping. More in-depth analyses of PNe (Hora et al. 1999; Davis et al. 2003) have revealed that in most cases where both the rotational and vibrational temperature of H$_2$ are around 2000 K, shock heating is the dominant excitation mechanism of IR lines. In order to confirm the shock scenario, we need a better understanding of the gas motions in the two objects, in addition to observations shortward of 2 $\mu$m.

The observed presence of both ionized species and molecules in the same aperture, and the small covering factor necessary to explain the nondetection of continuum pumped lines confirms the current view of molecules residing in globules surrounded by an ionized medium, the source of the exciting Ly$\alpha$ radiation (Meaburn & Lopez 1993; Huggins et al. 2002; Speck et al. 2003). The presence of globules helps the survival of hydrogen molecules, shielded from photodissociation by hard stellar radiation. Overall, the H$_2$ column density derived for the Ly$\alpha$ pumping model is much higher than the one derived from absorption spectra ($10^{18}$ vs. $10^{16}$ cm$^{-2}$), suggesting different properties of the regions they are probing. Taking into account that the globule size in NGC 6853 is likely to be less than 10$^0$, the FUSE observations average between high- and low-density areas, where the low-density regions are thought to have a negligible extinction. The low slit filling fraction for the Ly$\alpha$ pumped radiation in both FUSE and HUT observations allows us to reconcile the derived value of a few times $10^{18}$ cm$^{-2}$ for the H$_2$ column density with columns of $10^{21}$ cm$^{-2}$ suggested for dense globules from visual extinction arguments (Bohlin et al. 1978; Meaburn & Lopez 1993).

4.1. Rovibrational Cascade Modified by Ly$\alpha$ Pumping

We constructed the rovibrational spectrum as a combination of a nonequilibrium cascade following Ly$\alpha$ pumping and a steady state emission due to the equilibrium distribution of molecules on the X$^1\Sigma^+_g$ state levels. For the nonequilibrium cascade, we start with the rates at which the X$^1\Sigma^+_g$ levels are populated following Ly$\alpha$ pumping and evaluate the line strengths according to the branching ratios. Collisional effects are ignored for the purpose of this estimate. As a proxy for the equilibrium populations for the steady state case we use the ground-state populations measured from absorption spectra and extrapolated to higher vibrational and rotational levels using a 2040 K thermal distribution with a total H$_2$ column density of $7.9 \times 10^{16}$ cm$^{-2}$. For this reason, hereafter we refer to this steady state model as thermal. The transition probabilities from Wolniewicz et al. (1998) are used to derive the output spectrum, shown in Figure 6. The solid black line contains contributions from both thermal and fluorescent pumping, convolved with a 15 $\AA$ Gaussian. Overplotted in red is the thermal contribution alone. The lines showing the largest contribution from fluorescent pumping are numbered, and their principal components are listed in Table 9. The line strengths are given as upper
The rovibrational cascade shows most of the Lyα pumping specific features in the visible and near-IR part of the spectrum. We find little deviation from a pure thermal emission longward of \( \sim 1 \mu \text{m} \). As a consequence, line pumped UV fluorescence might be present even when the measured IR line ratios around 2 \( \mu \text{m} \) are consistent with a thermal distribution of the \( \text{H}_2 \) molecules in the ground electronic state.

The detection of these lines represents an observational challenge from the ground. In Figure 8 the positions of the strongest predicted lines are indicated on the airglow emission spectrum reconstructed from Ultraviolet-Visual Echelle Spectrograph (UVES) observations (Hanuschik 2003) at a resolution of 15 Å to match the resolution of our model. The lack of airglow features in the 0.577–0.583 \( \mu \text{m} \) interval is due to the chip gap in the UVES spectrum. However, Osterbrock et al. (1996) showed that there are no lines identified in this region. The rovibrational cascade at a level of a few times \( 10^{-5} \) ergs \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \mu \text{m}^{-1} \) is about 1000 times smaller than the typical airglow lines and continuum in the 0.56–1.015 \( \mu \text{m} \) interval. A much lower background level and a higher spectral resolution (\( \sim \) a few angstroms) may allow the detection of the (9–3) S(4) line at 5810.36 Å and the (8–3) S(6) line at 6681.40 Å (Fig. 7).

Lyα pumping redistributes molecules from the \((v''', J''')\) levels (2, 6) and (2, 5) among the rovibrational levels of the ground state. However, at the level of the observed UV fluorescence, a significant deviation from the thermal populations of the \((v''', J''')\) levels (2, 6) and (2, 5) is not found. Correcting for the rovibrational transitions that repopulate these levels, we find that the population decrease relative to the thermal distribution \( \left( \Delta N_{v''}/N_{v''}^{\text{thermal}} \right) \) is about 0.0107 and 0.0012 for the (2, 6) and (2, 5) levels, respectively. We find more significant deviations from a thermal population among the rotational levels of the \( v'' = 0 \) state. These are likely to be affected also by collisional redistribution and do not match the deviations measured from UV absorption spectra (S. R. McCandliss et al. 2006, in preparation). Deviations in the populations of higher vibrational levels \((v'' > 2)\) are predicted to result in a specific signature in the rovibrational spectrum (Fig. 6).

5. CONCLUSION

Line pumping by Lyα is required to qualitatively explain the \( \text{H}_2 \) emission features in the far UV spectra of NGC 6853 and NCG 3132. The observed \( \text{H}_2 \) fluorescence gives us valuable information about the conditions of the radiation field and dynamics of the molecular gas in PNe. The input parameters are similar for both objects, suggesting that we do not see an isolated

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**TABLE 9**

| Reference Number | Line ID | Wavelength (Å) | Brightness (R) |
|------------------|---------|----------------|---------------|
| 1…………………... | (6–1) S(6) | 5689.17 | 0.022 |
| 2………………... | (9–3) S(4) | 5810.36 | 0.007 |
| 3………………... | (7–2) S(4) | 6096.58 | 0.034 |
| 4………………... | (7–2) S(6) | 6145.49 | 0.058 |
| 5………………... | (8–3) S(3) | 6607.73 | 0.015 |
| 6………………... | (8–3) S(4) | 6612.89 | 0.047 |
| 7………………... | (8–3) S(6) | 6681.40 | 0.061 |
| 8………………... | (5–1) S(6) | 6726.46 | 0.040 |
| 9………………... | (5–1) S(6) | 6732.89 | 0.037 |
| 10…………….. | (9–4) S(4) | 7224.75 | 0.024 |
| 11…………….. | (6–2) S(4) | 7231.36 | 0.082 |
| 12…………….. | (6–2) S(3) | 7250.86 | 0.036 |
| 13…………….. | (6–2) S(6) | 7251.65 | 0.134 |
| 14…………….. | (7–3) S(4) | 7818.21 | 0.160 |
| 15…………….. | (7–3) S(6) | 7833.48 | 0.064 |
| 16…………….. | (7–3) S(6) | 7857.03 | 0.240 |
| 17…………….. | (3–0) S(6) | 7871.01 | 0.120 |
| 18…………….. | (3–0) S(4) | 7934.81 | 0.150 |
| 19…………….. | (4–1) S(4) | 8469.30 | 0.255 |
| 20…………….. | (8–4) S(6) | 8572.68 | 0.189 |
| 21…………….. | (4–1) S(2) | 8615.89 | 0.093 |
| 22…………….. | (5–2) S(6) | 9037.36 | 0.203 |
| 23…………….. | (5–2) S(4) | 9081.00 | 0.252 |
| 24…………….. | (4–1) Q(6) | 9228.52 | 0.034 |
| 25…………….. | (5–2) Q(4) | 9228.82 | 0.113 |
| 26…………….. | (9–5) S(4) | 9333.02 | 0.069 |
| 27…………….. | (9–5) S(6) | 9333.40 | 0.021 |
| 28…………….. | (5–2) S(1) | 9339.80 | 0.065 |
| 29…………….. | (6–3) S(5) | 9758.45 | 0.019 |
| 30…………….. | (6–3) S(6) | 9760.54 | 0.486 |
| 31…………….. | (6–3) S(4) | 9787.93 | 0.345 |
| 32…………….. | (6–3) S(3) | 9847.38 | 0.170 |
| 33…………….. | (6–3) S(1) | 10052.00 | 0.092 |
| 34…………….. | (5–2) Q(6) | 10095.00 | 0.070 |

**Note.**—Thermal contribution not included.

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**Fig. 7.**—Airglow spectrum reconstructed from UVES data (Hanuschik 2003), with a resolution of 15 Å. The positions of the strongest lines following Lyα pumping are indicated by the vertical lines, numbered as in Fig. 6.
phenomenon. The UV H$_2$ spectrum is likely due to thermally excited molecular hydrogen, shielded from the UV continuum inside globules surrounded by strong nebular Ly$_\alpha$/C$\text{II}$ emission. We emphasize that while molecular hydrogen pumping by Ly$_\alpha$/C$\text{II}$ shows strong features in UV spectra, it could remain unobservable in the IR and visible. UV observations are thus a requirement for investigating this process in various environments where hot H$_2$ is exposed to the presence of Ly$_\alpha$.

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