AN 8.5 GHz Arecibo Survey of Carbon Recombination Lines Toward Ultracompact H II Regions: Physical Properties of Dense Molecular Material

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ABSTRACT

We report here on a survey of carbon recombination lines (RLs) near 8.5 GHz toward 17 ultracompact H II regions (UCHs). Carbon RLs are detected in 11 directions, indicating the presence of dense photodissociation regions (PDRs) associated with the UCHs. In this paper, we show that the carbon RLs provide important, complementary information on the kinematics and physical properties of the ambient medium near UCHs. Non-LTE models for the carbon line-forming region are developed, assuming that the PDRs surround the UCHs, and we constrained the model parameters by multifrequency RL data. Modeling shows that carbon RL emission near 8.5 GHz is dominated by stimulated emission, and hence we preferentially observe the PDR material that is in front of the UCH continuum. We find that the relative motion between ionized gas and the associated PDR is about half that estimated earlier, and it has an rms velocity difference of 3.3 km s\(^{-1}\). Our models also give estimates for the PDR density and pressure. We found that the neutral density of PDRs is typically >5 \(\times 10^5\) cm\(^{-3}\), and UCHs can be embedded in regions with high ambient pressure. Our results are consistent with a pressure-confined H II region model in which the stars are moving relative to the cloud core. Other models cannot be ruled out, however. Interestingly, in most cases, the PDR pressure is an order of magnitude larger than the pressure of the ionized gas. Further investigation is needed to understand this large pressure difference.

Subject headings: H II regions — ISM: general — line: formation — radio lines: ISM — stars: formation — surveys

1. INTRODUCTION

Observations of molecular lines toward ultracompact H II regions (UCHs) have shown that the natal clouds harboring the H II regions have densities >10\(^5\) cm\(^{-3}\) and temperatures between 100 and 200 K (see Churchwell 2002). The presence of such dense clouds has other observable effects. In particular, far-ultraviolet (FUV) photons (6.0–13.6 eV) from OB stars should produce photodissociation regions (PDRs) in the neutral material close to the UCH (see review by Hollenbach & Tielens 1997). Gas-phase carbon in these regions is ionized by photons in the energy range 11.3–13.6 eV. The physical conditions in these PDRs are ideally suited for producing observable radio recombination lines (RLs) of carbon (Natta et al. 1994; S. Jeyakumar et al. 2005, in preparation).

To date, most objects that have been searched for carbon RL emission are extended H II regions. These H II regions are often density bound, and the molecular densities near them are low. Thus, not surprisingly, these searches have detected carbon lines only toward a few extended H II regions. UCHs form in or near dense molecular material, and hence they appear to be ideal targets for detecting carbon RLs. A handful of recent Very Large Array observations were successful in detecting carbon RLs toward UCHs. For example, observations toward W48A and W49 have detected, respectively, the 76\(\alpha\) (14697.314 MHz) and 92\(\alpha\) (8313.528 MHz) transitions of carbon (Roshi et al. 2005; C. G. De Pree et al. 2005, in preparation). The angular resolutions of these observations (5\('\) and 2\('\), respectively) were sufficient to infer that the line emission is associated with the UCHs. Moreover, the detected RLs have velocities similar to that of the molecular clouds harboring the UCHs, implying that the line-forming region is embedded in the dense material near the H II regions.

Multifrequency carbon RL observations from PDRs associated with UCHs can be used (1) to estimate the physical properties of the dense molecular material (S. Jeyakumar et al. 2005, in preparation) and (2) to test whether UCHs are pressure confined (Roshi et al. 2005). With these aims, we made a survey of carbon RLs near 8.5 GHz with the Arecibo telescope\(^2\) toward 17 UCHs. The source selection was made such that at least one source from each of the six morphological types suggested by Wood & Churchwell (1989b) and Kurtz et al. (1994) for UCHs is observed in the survey (see Table 1). Another criterion used for

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selection was that the continuum flux densities at 2 cm of the UCHs are >150 mJy (Wood & Churchwell 1989b; Kurtz et al. 1994). In § 2 we discuss the observations and data analysis procedure. The results of the survey are given in § 3. In § 4 we present the details of modeling of the carbon RL emission toward a selected subset of UCHs from our sample. Our conclusions are given in § 5.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were made at frequencies near 8.5 GHz with the Arecibo Telescope on 2003 May 30 through June 4. At the observed frequency, the telescope has a beam width (FWHM) of 28″. The wide bandwidth of the 8–10 GHz receiver system of the telescope was used to simultaneously observe four RL transitions (89α, 90α, 91α, and 92α) of carbon, hydrogen, and helium from two polarizations. In addition to these lines, the H113/β line (8878.730 MHz) was present in the frequency band of the spectrometer used for observing the 90α RL transitions. The autocorrelation spectrometer was configured in the four-subband mode to observe the four RL transitions. The transitions were selected such that the frequency range was free of radio frequency interference (RFI). We used 25 MHz bandwidth for each subband, which corresponds to a velocity range of ~840 km s⁻¹. This velocity range was adequate to observe RLs of carbon, helium, and hydrogen in each subband. We selected nine-bit sampling in the correlator to minimize effects due to RFI and to maximize the sensitivity of the observations. In the chosen configuration, the correlator provides 1024 spectral channels for each subband and for each polarization. Before observing the target sources, the setup was tested by observing the “extended” H α region G43.17+0.0 (Lockman 1989).

Our observations were one of the first scientific uses of the 8–10 GHz system, and hence there were several factors affecting telescope performance. Some of these factors are (1) an inaccurate telescope pointing model and (2) irregularities of the primary surface panel settings. Moreover, we had to use a “gain curve” that is poorly sampled in azimuth and elevation. The gain curve essentially provides the telescope gain (i.e., antenna temperature in kelvins per jansky) for different azimuths and zenith angles. This curve is needed to calibrate the observed spectra in janskys, since the gain of the Arecibo telescope is a function of azimuth and zenith angle. The gain curve is derived from observations toward a set of calibrator sources. We had to use data toward calibrator sources observed during the period 2003 March 1 to July 19 to derive the gain curve. The number of calibrators observed in this period was not large enough to provide good sampling of the telescope gain over azimuth and zenith angle. (Unfortunately, the receiver system was modified a few weeks after our observations so we could not improve on this gain curve.) During the 15 months subsequent to our observations, the performance of the 8–10 GHz system, the data quality, and the calibration procedure have all been significantly improved. Because of the performance limitations during our observations, however, we were forced to devise several analysis procedures in order to minimize the calibration errors. In addition to the software provided by Arecibo observatory, we developed programs in IDL to implement these procedures.

Since the telescope pointing model was not accurate, we observed calibrator sources B1843+098, B1857+129, and B2018+295 at intervals of about 45 minutes. We made azimuth–zenith angle continuum cross scans in order to measure pointing offsets. These offsets were used to correct the telescope pointing before observing the target sources. We found that the pointing offset was as large as 16″ (~0.6 x FWHM beam width) in some cases. Because the position could, of course, not be corrected during observations, pointing errors have resulted in an additional uncertainty in the amplitude calibration of our spectra. We estimate below that the RL amplitudes reported here have an error of 20%.

Careful bandpass calibration is important for our observations, since the RL flux density is less than 1% of the system equivalent flux density. To do this we observed a target source for 5 minutes, then switched to an off-source position and acquired data for the same amount of time. The off-source position was selected such that it followed the same azimuth–zenith angle track as that of the target source during the integration. After each on- and off-source measurement pair, spectra were taken with a noise calibration signal, turned on and off for 30 s, respectively. These data were used to derive the system temperature.

We configured the spectrometer to have an integration time of 1 s. This short averaging time was selected in case the spectra were affected by RFI. Examination of the data showed that the four bands were not affected by any RFI. The spectrometer provides the Fourier transforms of the measured autocorrelation function after applying uniform weighting. The spectral resolution achieved is about 1 km s⁻¹, which is adequate to resolve the carbon RLs.

The noise calibration scans and the gain curve were used to calibrate the spectrum in units of janskys. We noticed that the total power in the 1 s integrations was not stable for some of the subbands. Therefore, we visually examined the calibrated spectra for relatively high rms and discrepant spectral baselines and excised these data. Less than 1% of the data were excised.

The velocity resolutions of the subbands were not the same because they are centered at different sky frequencies. For the carbon RLs observed here the velocity resolution can change by as much as 10%. Moreover, the spectra of the four subbands are not sampled at the same velocities. Since the spectra were obtained by Fourier transforming the measured autocorrelation functions with uniform weighting, the filter response of the spectrum was a sinc function. We therefore resampled the spectra using sinc interpolation in order to have an identical velocity sampling for all subbands. We referenced all subbands to the velocity scale and resolution of the spectrum corresponding to the 89α transition. A demonstration of our resampling process is given in Figure 1, where the average spectrum obtained toward G61.48+0.09 and the resampled average spectra of the four subbands are shown. The velocity range is restricted to show the carbon RL, which has the smallest line width (4.7 km s⁻¹) and hence is affected most by any error in the resampling processes. The good agreement between the carbon RL profiles proves the efficacy of the resampling process. The four resampled spectra of a scan were then averaged to produce a single calibrated spectrum for each polarization.

We examined the amplitude of the hydrogen RLs in the individual on/off pairs for each source. For some sources the hydrogen RL amplitude changed during the integration. Since the RL intensity is not expected to change, this variation in line amplitude is due to pointing errors and/or errors in the estimated antenna gain. To minimize the error in the final spectrum and to maximize the signal-to-noise ratio, we weighted the spectrum of each scan by the ratio of the hydrogen RL amplitude to the spectral variance before averaging. The variance was estimated using spectral values in the velocity range where RLs were not present and after removing a residual baseline. During the observations we choose to apply a Doppler correction for each subband separately, and hence the spectra corresponding to different scans could be averaged without any further velocity shift. The frequency offset used for each subband was based on the rest frequency of the carbon RL observed in that subband.
The spectral baselines of the final calibrated spectra were fit with a third-order (or less) polynomial model using only the line-free channels. The continuum flux density was determined to be the mean value of this baseline model. The spectral line profiles were modeled using a minimum number of Gaussian components that were able to fit the hydrogen, helium, carbon, and H133/β lines without any constraints on the model parameters. In one object there was evidence for a weak heavy ion (heavier than C+ ion) RL in the residuals. The Gaussian parameters of this profile were obtained by keeping the model parameters of the other four RLs constant.

The error in the line flux density in the final average spectrum can be estimated by comparing the hydrogen RL amplitude in the final spectrum with that obtained from individual scans. The comparison showed that the line flux density was within 15%–18% of the maximum RL amplitude observed for a source but clearly biased toward lower values. However, the spectrum with maximum amplitude itself may not have the correct flux density in all cases, since sampling of the gain curve is nonoptimal. So we further compared the continuum flux densities of two sources (G32.80+0.19 and G70.29+1.60) with those obtained from existing 3.6 cm interferometric images (see Table 3). The continuum flux densities obtained from our observations (see Table 2) were measured with respect to the off-source position used for bandpass calibration. The two sources were selected on the basis of negligible sky contribution to the continuum emission at the off-source position, as inferred from existing continuum surveys (Reich et al. 1990; Altenhoff et al. 1979). Neglecting the small wavelength difference, the flux densities obtained from our observations are within 10% of those estimated from interferometric data. On the basis of this comparison and the lower line flux densities in the final spectra compared to the observed maximum values, we estimate a 1 σ error of 20% for all RL flux densities obtained from our survey data.

3. RESULTS

Table 1 gives the source names, morphological type, and J2000 coordinates of the 17 UCHs observed in the survey. The effective integration time given in Table 1 is 8 times the actual on-source observing time, since the final spectra are obtained by averaging all four RL transitions from two polarizations. The calibrated spectra toward the observed sources are shown in Figures 2a and 2b. Table 2 gives the line parameters obtained from Gaussian modeling of the final spectra together with the 1 σ error on these parameters provided by the nonlinear least-squares

| Source Name | Type a | R.A. (J2000.0) | Decl. (J2000.0) | Integration Time (minutes) |
|-------------|--------|---------------|---------------|----------------------------|
| G32.80+0.19 | b      | 18 50 30.9    | 00 02 00      | 40                         |
| G34.26+0.15 | b      | 18 53 18.5    | 01 14 59      | 40                         |
| G35.20−1.74 | C      | 19 01 46.5    | 01 13 24      | 80                         |
| G35.57−0.03 | b      | 18 56 22.6    | 02 20 27      | 40                         |
| G37.87−0.40 | C      | 19 01 53.6    | 04 12 49      | 80                         |
| G41.74+0.10 | CH     | 19 07 15.5    | 07 52 44      | 40                         |
| G43.24−0.05 | b      | 19 10 33.5    | 09 08 25      | 320                        |
| G43.89−0.78 | C      | 19 14 26.2    | 09 22 34      | 40                         |
| G45.12+0.13 | C      | 19 13 27.8    | 10 53 37      | 120                        |
| G45.45+0.06 | b      | 19 14 21.4    | 11 09 15      | 160                        |
| G45.47+0.05 | I      | 19 14 25.6    | 11 09 26      | 40                         |
| G48.61−0.02 | b      | 19 20 31.2    | 13 55 23      | 120                        |
| G50.32+0.68 | S      | 19 21 27.6    | 15 44 21      | 40                         |
| G60.88−0.13 | G      | 19 46 19.9    | 24 35 24      | 240                        |
| G61.48+0.09 | S      | 19 46 48.3    | 25 12 48      | 160                        |
| G70.29+1.60 | CH     | 20 01 45.7    | 33 32 43      | 120                        |
| G70.33+1.59 | U      | 20 01 54.1    | 33 34 15      | 120                        |
| G43.17+0.00 | d      | 19 10 15.7    | 09 06 06      | 40                         |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a Morphological types of UCHs are C, cometary; CH, core-halo; I, irregular; S, spherical; G, Gaussian; and U, unresolved. The types of the observed UCHs are taken from Wood & Churchwell (1989b) and Kurtz et al. (1994).

b Multiple sources with different morphological types are present within the observed beam.

c An evolved H II region is present within the observed beam.

d Extended H II region (Lockman 1989).
Fig. 2.—RL spectra toward 11 UCHs for which carbon RLs have been detected in the Arecibo survey. The spectra are obtained by averaging four RL transitions (89\(\alpha\), 90\(\alpha\), 91\(\alpha\), and 92\(\alpha\)) near 8.5 GHz. The strongest line in the figure is the hydrogen RL. The carbon, helium, H113\(\beta\), and heavy-ion RLs are marked in the spectra where these lines are detected. The spectrum obtained toward the extended H ii region G43.17+0.00 is also shown.
Fig. 2.—Continued
| Source Name       | $S^*$ (Jy) | rms (mJy) | Transition | $S_L$ (mJy) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) |
|-------------------|------------|-----------|------------|-------------|-------------------------------|----------------------------|
| G32.80+0.19       | 3.8        | 3.5       | C          | 16.2 (2.4)  | 13.5 (0.6)                   | 7.5 (1.3)                  |
|                   |            |           | He         | 29.6 (1.3)  | 15.1 (0.6)                   | 24.3 (1.3)                 |
|                   |            |           | H          | 326.5 (1.2) | 15.3 (0.1)                   | 30.1 (0.1)                 |
|                   |            |           | H113/$\beta$ | 57.4 (1.8) | 12.2 (0.5)                   | 35.4 (1.3)                 |
| G34.26+0.15       | 3.5        | 2.9       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | 7.9 (0.6)   | 41.7 (1.9)                   | 53.2 (4.4)                 |
|                   |            |           | H          | 47.2 (1.9)  | 51.0 (0.3)                   | 26.5 (1.0)                 |
|                   |            |           | H          | 85.4 (1.7)  | 36.0 (0.4)                   | 64.9 (0.6)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G35.20−1.74       | 4.1        | 2.6       | C          | 25.2 (2.0)  | 43.3 (0.3)                   | 6.3 (0.6)                  |
|                   |            |           | He         | 33.4 (1.3)  | 49.2 (0.3)                   | 15.1 (0.7)                 |
|                   |            |           | H          | 372.0 (1.0) | 47.8 (0.04)                  | 27.5 (0.1)                 |
|                   |            |           | H113/$\beta$ | 81.9 (1.6) | 45.3 (0.3)                   | 30.1 (0.7)                 |
| G35.57−0.03       | 0.4        | 2.3       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 22.0 (0.6)  | 52.3 (0.4)                   | 30.9 (0.9)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G37.87−0.40       | 3.0        | 2.1       | C          | 8.0 (0.7)   | 56.8 (0.6)                   | 14.0 (1.5)                 |
|                   |            |           | He         | 16.8 (0.4)  | 59.7 (0.5)                   | 31.7 (1.3)                 |
|                   |            |           | H          | 93.0 (2.7)  | 60.3 (0.1)                   | 26.1 (0.4)                 |
|                   |            |           | H          | 104.5 (2.7) | 56.6 (0.1)                   | 55.1 (0.5)                 |
|                   |            |           | H113/$\beta$ | 42.7 (1.3) | 56.4 (0.6)                   | 38.7 (1.4)                 |
| G41.74+0.10       | 0.1        | 1.8       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 7.7 (0.5)   | 12.9 (1.0)                   | 34.0 (2.3)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G43.24−0.05       | 0.7        | 0.8       | C          | 3.9 (0.5)   | 5.9 (0.4)                    | 6.2 (0.9)                  |
|                   |            |           | He         | 6.0 (0.3)   | 10.0 (0.4)                   | 15.8 (0.9)                 |
|                   |            |           | H          | 73.3 (0.2)  | 9.6 (0.04)                   | 24.1 (0.1)                 |
|                   |            |           | H113/$\beta$ | 18.2 (0.6) | 5.7 (0.5)                    | 29.9 (1.2)                 |
| G43.89−0.78       | 0.2        | 1.9       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 18.4 (0.5)  | 54.4 (0.4)                   | 25.9 (0.8)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G45.12+0.13       | 1.9        | 1.3       | C          | 4.9 (0.6)   | 55.7 (0.8)                   | 12.9 (1.9)                 |
|                   |            |           | He         | 8.9 (0.4)   | 58.5 (0.7)                   | 30.1 (1.8)                 |
|                   |            |           | H          | 72.5 (1.2)  | 57.1 (0.1)                   | 27.4 (0.4)                 |
|                   |            |           | H          | 32.7 (1.3)  | 59.7 (0.3)                   | 69.5 (1.2)                 |
|                   |            |           | H113/$\beta$ | 21.9 (2.2) | 51.8 (1.4)                   | 27.6 (3.2)                 |
| G45.45+0.06       | 2.6        | 1.6       | C          | 3.5 (0.8)   | 59.0 (1.2)                   | 9.6 (2.9)                  |
|                   |            |           | He         | 23.9 (0.6)  | 54.6 (0.3)                   | 20.3 (0.7)                 |
|                   |            |           | H          | 245.8 (0.5) | 54.7 (0.03)                  | 27.6 (0.06)                |
|                   |            |           | H113/$\beta$ | 58.4 (2.5) | 51.3 (0.7)                   | 33.0 (1.6)                 |
| G45.47+0.05       | 0.2        | 2.2       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 12.8 (0.5)  | 62.9 (0.6)                   | 31.6 (1.5)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G48.61+0.02       | 0.5        | 1.2       | C          | 5.2 (1.0)   | 18.4 (0.3)                   | 3.3 (0.7)                  |
|                   |            |           | He         | 4.5 (0.5)   | 15.8 (0.7)                   | 11.7 (1.6)                 |
|                   |            |           | H          | 50.5 (0.4)  | 16.7 (0.1)                   | 23.5 (0.2)                 |
|                   |            |           | H113/$\beta$ | 18.1 (1.1) | 12.4 (0.9)                   | 30.5 (2.2)                 |
| G50.32+0.68       | 0.1        | 2.0       | C          | ...         | ...                           | ...                       |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 12.0 (0.5)  | 26.9 (0.5)                   | 25.7 (1.2)                 |
|                   |            |           | H113/$\beta$ | ...         | ...                           | ...                       |
| G60.88−0.13       | 0.2        | 1.0       | C          | 11.5 (0.7)  | 22.0 (0.1)                   | 4.5 (0.3)                  |
|                   |            |           | He         | ...         | ...                           | ...                       |
|                   |            |           | H          | 35.2 (0.3)  | 18.3 (0.1)                   | 20.7 (0.2)                 |
|                   |            |           | H113/$\beta$ | 8.9 (0.8)  | 12.7 (1.4)                   | 30.6 (3.3)                 |
| G61.48+0.09       | 4.0        | 1.6       | C          | 45.5 (1.7)  | 21.3 (0.1)                   | 4.7 (0.2)                  |
|                   |            |           | He         | 27.2 (0.9)  | 28.8 (0.3)                   | 16.1 (0.6)                 |
|                   |            |           | H          | 368.5 (0.7) | 26.4 (0.03)                  | 26.3 (0.1)                 |
|                   |            |           | H113/$\beta$ | 78.0 (3.7) | 23.2 (0.8)                   | 33.4 (1.8)                 |
| S (?)b            | 7.2        | 2.4       | C          | 7.2 (2.4)   | 21.3 (0.4)                   | 2.4 (0.9)                  |
focusing routine. The rms is obtained from the final spectrum using values in the velocity range free of any RL emission. The continuum flux densities of the observed sources, which are measured with respect to the off-source position used for band shape measurement, are also listed. This flux density is the mean value of the polynomial baseline model removed from the final calibrated spectra (see § 2). Note that these values, in all cases, are not the true density of the observed sources, since continuum emission may be present in the off-source position.

As mentioned above, we observed the H II region G43.17+0.0 to test the observing setup. We have detected hydrogen, helium, carbon, and H113/β lines toward G43.17+0.0, indicating that our observing procedures were correct. The coordinates of the H II region and line parameters are given in Table 1. The final spectrum obtained toward G43.17+0.0 is shown in Figure 2b. Since G43.17+0.0 is an extended H II region, we do not discuss this source further.

3.1. Carbon Recombination Lines

Carbon RLs were detected toward 11 UCHs (65% detection rate) out of the 17 observed sources. The detection of carbon RLs toward a large number of UCHs indicates that a majority of these H II regions have associated dense PDRs. The sources where carbon RLs were not detected probably also have associated dense PDRs; we believe that the nondetections are due to sensitivity limitations. The ratio of carbon to hydrogen RLs obtained from the 11 detections has a mean value of 0.11 (1 σ error 0.09). The expected carbon line flux density estimated using this ratio and the detected hydrogen line flux density is less than the rms noise in the spectrum of the sources where carbon RLs were not detected. Thus, we conclude that our data are consistent with the hypothesis that all UCHs in our survey have associated dense PDR material.

On the basis of the continuum morphology of UCHs, Wood & Churchwell (1989b) and Kurtz et al. (1994) have classified these regions into seven types: unresolved/spherical, cometary, core-halo, Gaussian, shell, multiple peak, and irregular. UCHs observed in this survey are selected from these different morphological types (see Table 1). Carbon lines have been detected toward UCHs belonging to all types except for the irregular morphologies. Observations toward a larger sample of UCHs are, however, needed to establish a definite relationship between the formation of PDRs and the morphology of UCHs.

The observed width of the carbon RLs ranges between 3 and 14 km s⁻¹, with a median value of 6.3 km s⁻¹. The expected thermal line width from these regions is <1.9 km s⁻¹ (corresponding to a gas temperature of 1000 K; Natta et al. 1994), indicating that nonthermal motions in the PDR dominate. Earlier observations of the NH3 (1, 1) transition toward UCHs showed that their line widths are typically between 1.5 and 4 km s⁻¹, with a median value of ~3 km s⁻¹ (Churchwell et al. 1990). Thus, the median width of carbon RLs is a factor of 2 larger than that of NH3 (1, 1). The line widths in both cases are dominated by nonthermal motion. Higher angular resolution observations are needed to understand the line width difference and the relationship between the molecular and carbon line-forming regions. The different line widths may indicate that the two lines originate from different regions. Carbon lines may originate from regions closer to the boundary of the UCH, as expected in a molecular cloud–H II region interface.

Figure 3 shows the relationship between the continuum and carbon RL flux densities observed toward UCHs. Carbon RL intensity clearly correlates well with the continuum emission. At 8.5 GHz, continuum emission originates from the ionized gas associated with the UCH, while carbon RLs originate from PDR gas outside the H II region. Thus, the correlation between the two observed quantities indicates stimulated emission of carbon lines by the background continuum radiation. This correlation confirms the result by Natta et al. (1994) that, near 8.5 GHz, carbon RL emission is dominated by stimulated emission (see also § 4).

The dominance of stimulated emission for carbon lines implies that the RLs near 8.5 GHz are detected from the PDR on the near side of the UCH. Furthermore, modeling of RL emission shows that the line intensity from the PDR at the far side would typically be a factor of 5 weaker than that originating from the front and hence is not detectable in the present observations (see § 4). We used this information to study the relative motion between the PDRs and UCHs (Roshi et al. 2005). The observed central velocity of the hydrogen line represents the mean velocity of the ionized gas with respect to the observer. Therefore, the difference between the central velocities of the carbon and hydrogen lines provides a measure of the relative motion of the PDR.
with respect to the ionized region. The velocity difference ranges between $-5.2$ and $+4.3$ km s$^{-1}$, with an rms value of $3.3$ km s$^{-1}$. Note that the mean error of the relative velocity is only $0.4$ km s$^{-1}$. Also, the rms velocity difference between the hydrogen and carbon RLs is 3 times larger than that of hydrogen and helium RLs (see § 3.2). Earlier studies of the relative motion between the ionized gas in compact H II regions and the molecular gas associated with them have shown velocity differences ranging between $-12$ and $+8$ km s$^{-1}$ (Forster et al. 1990). Our observations show a velocity difference that is about half that inferred from molecular line data.

### 3.2. Hydrogen, Helium, H113β, and Heavy-Ion Recombination Lines

Hydrogen RLs were detected toward all the observed sources. The line profiles can in most cases be modeled by a single-component Gaussian. For four sources (G34.26+0.15, G37.87–0.40, G45.12+0.13, and G70.29+1.60), the observed line profile is better approximated by a two-component Gaussian (see Table 2). Line width ranges between 23.5 and 69.7 km s$^{-1}$. The broad (>50 km s$^{-1}$) hydrogen lines show non-Gaussian profiles. Such broad lines had previously been observed toward UCHs (Jaffe & Martin-Pintado 1999; De Pree et al. 2004). Helium and H113β RLs were detected toward sources where the rms noise in the spectrum is less than about 10% of the peak hydrogen line flux density, G60.88–0.13 is an exception: the H113β and carbon line were detected toward this source, but no helium line was detected. A heavy-ion RL was detected toward the source G61.48+0.09.

Since helium and hydrogen RLs originate from the same ionized gas, no difference in their central velocities is expected. The relative velocity ranges between $-1.8$ and $+2.3$ km s$^{-1}$ with an rms velocity difference of $1.1$ km s$^{-1}$. Since the mean error of the relative velocities is $0.6$ km s$^{-1}$, we conclude that this rms value is not significant. (Note that when multiple hydrogen RL components are present we used the mean velocity of hydrogen RL components to compute the relative velocity.) The velocity differences between the hydrogen and H113β RLs show a mean value of $3.6$ km s$^{-1}$. This velocity difference probably originates in the fact that the H113/3 line is blended with the H129γ line. We have modeled noiseless Gaussian profiles assuming that the H113/3 transition is 2.5 times more intense than the H129γ line, a shift in LSR velocity of 15 km s$^{-1}$ between the two line centers (based on the known frequencies), and that both lines have an FWHM of 25 km s$^{-1}$. A single Gaussian component model fit to the blended profile produces a shift in velocity of $3.67$ km s$^{-1}$, consistent with our results.

### 4. Physical Properties of the PDRs

The physical properties of the PDR can be determined by modeling multifrequency carbon line data (Natta et al. 1994; S. Jeyakumar et al. 2005, in preparation). The observed carbon line intensity is a function of the background radiation intensity, since the carbon line emission is dominated by stimulated emission (Natta et al. 1994). For the present case, the background radiation is due to the thermal continuum emission from the UCHs. Therefore, for modeling, we carefully selected a subset of UCHs from our sample whose properties could be estimated with data available in the literature. Table 3 summarizes the parameters of the UCHs selected for modeling. Interferometric images of the selected sources near 3.6 cm wavelength with visibilities measured at an angular scale comparable to the Arecibo beam are available (Afflerbach et al. 1996; Kurtz et al. 1994). The continuum flux density and angular size of the UCHs are obtained from these images. Note that for sources where both compact and extended emission are present the angular size is roughly obtained from the half-power contour of the extended emission. Thus, these source sizes are different from the values given by Afflerbach et al. (1996) in their paper. Afflerbach et al. (1996) have estimated the electron temperature, $T_e$, of the ionized gas in most of the selected UCHs. We assumed a temperature of $10^4$ K for the source G43.24–0.05, since no temperature estimate is available. Using these temperatures and angular sizes, we derive the emission measures (EMs) of the UCHs that are consistent with the observed continuum flux density at 3.6 cm. We assume that the ionized region has cylindrical geometry with length equal to the diameter to derive the EM. (The correction factor given by Mezger & Henderson [1967] that needs to be used while obtaining the EM for such geometry is not applied, since for most sources the flux density distribution cannot be approximated as a simple Gaussian.) These EMs, along with angular sizes and distances to the sources, are used to estimate the electron density, $n_e$.

The PDR parameters that determine the carbon line intensity are gas temperature, $T_{PDR}$, electron density, $n_{ePDR}$, and PDR thickness along the line of sight, $l$. We considered homogeneous slabs of carbon line-forming region in front and back of the UCHs to estimate the RL emission. The line brightness temperature, $T_{LB}$, due to the slab in the front side is given by (Shaver 1975)

$$
T_{LB} = T_{\text{bg},\nu} e^{-\tau_{L\nu}}(e^{-\tau_{C\nu}} - 1) + T_{\text{PDR}} \left[ \frac{b_m \tau_{L\nu} + \tau_{C\nu}}{\tau_{L\nu} + \tau_{C\nu}} \left( 1 - e^{-(\tau_{L\nu} + \tau_{C\nu})} \right) - (1 - e^{-\tau_{C\nu}}) \right],
$$

(1)

where $T_{\text{bg},\nu}$ is the background radiation temperature and $\tau_{C\nu}$ is the continuum optical depth of the PDR. The non-LTE line

![Graph of Continuum flux density vs. Carbon line flux density](image-url)
optical depth of the spectral transition from energy state \( m \) to \( n \), \( \tau_{L_{L}} = \tau_{L_{L}}^{UC} = b_{n} \rho_{n} \tau_{L_{L}}^{UC} \), where \( \tau_{L_{L}}^{UC} \) is the LTE line optical depth and \( b_{n} \) and \( \rho_{n} \) are the departure coefficients of state \( n \). For the PDR, \( \tau_{L_{L}}^{UC} \propto n_{C}^{-1} \), where \( n_{C} \) is the carbon ion volume number density in the PDR. For the present calculations we assumed that \( n_{C}^{PDR} = n_{C} \), so \( \tau_{L_{L}}^{PDR} \propto n_{C}^{-1} \). Thus, for a homogeneous PDR, the electron density provided by the modeling will be the true electron density. However, for an inhomogeneous PDR, the actual electron density depends on just how clumpy the PDR is and the model value will be the square root of the second moment of the spatial distribution of electron density. The background temperature is given by

\[
T_{0bg, r} = T_{e} \left( 1 - e^{-\tau_{UCH}^{L}} \right),
\]

where \( \tau_{UCH}^{L} \) is the continuum optical depth of the UCH. The line temperature from the PDR on the far (back) side is obtained from equation (1) by setting \( T_{0bg, r} = 0 \). The line brightness temperature is finally converted to flux density using the source angular size given in Table 3.

Modeling starts with the computation of the non-LTE departure coefficients for a given electron density, gas temperature, and background radiation field. The coefficients are obtained using the program developed originally by Brocklehurst & Salem (1977) and later modified by Payne et al. (1994). These coefficients are then used to estimate the carbon line flux density as a function of frequency. We combined our data at 8.5 GHz with the existing RL data at 4.8 GHz to constrain the electron density and PDR thickness for a given gas temperature. The 4.8 GHz data (Araya et al. 2002; Watson et al. 2003) are listed in Table 3. We found that, for a given temperature, the electron density and PDR thickness can be well constrained using the data at these two frequencies. Particularly, the upper limit near 4.8 GHz provides a stringent lower limit on the electron density in the PDR (see also § 4.2).

Typically, the PDR gas temperature is in the range \( 300–1000 \) K (Natta et al. 1994). Table 4 lists the PDR electron density and thickness for temperatures of 300 and 500 K. Note that for higher gas temperatures the estimated electron density will be larger. The carbon RL flux densities predicted by the Table 4 models are shown in Figure 4, which plots for each source the model carbon line brightness temperature as a function of frequency. The model electron densities are converted to neutral densities using the cosmic abundance of carbon \( \left( 3.9 \times 10^{-4} \right) \) (Morton 1974) and a depletion factor of 25% (Natta et al. 1994). The neutral density, \( n_{H} \) (number density of hydrogen atoms), is in most cases greater than \( 5 \times 10^{8} \) cm\(^{-3} \) (see Table 4).

An important inference from modeling is the dominance of stimulated emission for carbon lines at frequencies \( \gtrsim 15 \) GHz. Line emission from the PDR slab in front of the UCH is amplified by the background continuum radiation from the ionized gas. The line flux density is typically 5 times larger than that from the PDR slab behind the UCH. Thus, the sensitivity of our observations is sufficient to detect only carbon line emission from

### Table 3

**Input Parameters for Modeling**

| Source Name      | \( D \) (kpc) | \( S_{b}^{a} \) (Jy) | \( S_{C110}^{b} \) (mJy) | Size (arcsec × arcsec) | \( T_{e} \) (K) | EM (pc cm\(^{-6} \)) | \( P_{UCH}^{c} \) (10\(^{-5} \) dyn cm\(^{-2} \)) | References\(^{d} \) |
|------------------|--------------|--------------------|----------------------|------------------------|----------------|---------------------|-------------------------------|------------------|
| G32.80+0.19     | 13.0         | 3.6                | <5.0                  | 15 × 7                 | 7600           | 17 × 10\(^{6} \)   | 7.1                          | 1, 4, 1, 1      |
| G37.87–0.40      | 9.2          | 4.2                | <5.0                  | 10 × 10                | 7800           | 21 × 10\(^{6} \)   | 16.1                         | 1, 4, 1, 1      |
| G43.24–0.05      | 11.6         | 0.4                | <1.4                  | 8 × 5                  | 10000          | 5 × 10\(^{6} \)    | 2.2                          | 2, 5, 6, 8, 9   |
| G45.12+0.13      | 6.0          | 6.1                | <6.0                  | 15 × 7                 | 8300           | 31 × 10\(^{6} \)   | 21.6                         | 3, 4, 1, 1      |
| G45.45+0.06      | 7.4          | 4.6                | <6.0                  | 20 × 20                | 9800           | 6 × 10\(^{6} \)    | 2.8                          | 1, 4, 1, 1      |
| G70.29+1.60      | 8.6          | 5.0                | <10.0                 | 10 × 5                 | 8500           | 56 × 10\(^{6} \)   | 123.8                        | 1, 4, 1, 1      |
| G70.33+1.59      | 8.6          | 1.6                | <10.0                 | 15 × 7                 | 9100           | 8 × 10\(^{6} \)    | 5.2                          | 1, 4, 1, 1      |

\(^{a}\) 3.6 cm continuum flux density and angular size are obtained from interferometric images.

\(^{b}\) C110 \( (4876.589 \) MHz) flux densities are taken from the literature.

\(^{c}\) The total pressure in UCH (see text).

\(^{d}\) References from which distance (\( d \)), 4.8 GHz line flux density (\( r \)), angular size of UCHs (\( s \)), and electron temperature (\( t \)) were obtained.

### Table 4

**Results of Modeling**

| Source Name      | \( n_{PDR}^{PDR} \) (cm\(^{-3} \)) | \( l \) (×10\(^{-3} \) pc) | \( n_{H} \) (×10\(^{6} \) cm\(^{-3} \)) | \( P_{PDR} \) (10\(^{-6} \) dyn cm\(^{-2} \)) | \( n_{PDR}^{PDR} \) (cm\(^{-3} \)) | \( l \) (×10\(^{-3} \) pc) | \( n_{H} \) (×10\(^{6} \) cm\(^{-3} \)) | \( P_{PDR} \) (10\(^{-6} \) dyn cm\(^{-2} \)) |
|------------------|-----------------------------------|-----------------------------|-----------------------------|-----------------------------------|-----------------------------------|-----------------------------|-----------------------------|-----------------------------------|
| G32.80+0.19      | 500                               | 1.4                         | 1.7                         | 2.2                               | 1000                             | 1.1                         | 3.4                         | 4.5                               |
| G37.87–0.40      | 110                               | 15.0                        | 0.4                         | 1.7                               | 120                              | 29.0                        | 0.4                         | 1.8                               |
| G43.24–0.05      | 300                               | 4.0                         | 1.0                         | 0.9                               | 300                              | 9.0                         | 1.0                         | 0.9                               |
| G45.12+0.13      | 40                                | 48.0                        | 0.1                         | 0.5                               | 40                               | 124.0                       | 0.1                         | 0.5                               |
| G45.45+0.06      | 20                                | 187.0                       | 0.1                         | 0.2                               | 30                               | 150.0                       | 0.1                         | 0.2                               |
| G70.29+1.60      | 300                               | 4.8                         | 1.0                         | 1.6                               | 350                              | 8.6                         | 1.2                         | 1.9                               |
| G70.33+1.59      | 150                               | 13.5                        | 0.5                         | 0.2                               | 170                              | 25.0                        | 0.6                         | 0.3                               |

\(^{a}\) The electron density, neutral density, and PDR pressure are lower limits.
Figure 4—Carbon line flux density as a function of frequency from models toward a subset of UCHs in the Arecibo survey. The electron temperatures used for modeling are 300 K (solid line) and 500 K (dashed line). The electron density and PDR thickness of the models are given in Table 4. The curves are obtained for model parameters that produce the observed carbon line flux density near 8.5 GHz (circle with ±1 σ error obtained from Gaussian modeling of line profiles) and are consistent with the 3 σ upper limit of carbon line flux density observed near 4.8 GHz.
the front of the UCH. As discussed in § 3.1, this fact can be used to study the relative motion of the PDR with respect to the UCH.

4.1. Pressure

We use the derived physical properties of the PDRs and the UCHs to estimate the pressure in these regions. The total gas pressure inside the UCH is the sum of thermal pressure and turbulent pressure. Because there are no direct measurements of the magnetic field strength in UCHs or PDRs, we do not include any contribution to the pressure from magnetic fields.

The total gas pressure is given by

$$P_{\text{UCH}} = \frac{2kneTe}{m_H} + \frac{n_He}{C_2^2}v_{\text{turb}}^2 \text{ dyn cm}^{-2},$$

(3)

where $k$ is Boltzmann’s constant, $\mu = 1.4$ is the effective mass in amu of a pure H + He gas with He fraction taken as 10% by number, $m_H$ is the hydrogen mass in grams, and $v_{\text{turb}}$ is the turbulent velocity inside the UCH in units of centimeters per second. The line profile due to turbulence is considered to be Gaussian with a FWHM of $v_{\text{turb}}$. We estimated $v_{\text{turb}}$ from the observed width of helium lines after removing the contribution due to thermal motion. (Hydrogen lines were not used, since some of the UCHs have multiple line components.) The values for electron density and temperature are taken from Table 3. The estimated pressures of the ionized gas in UCHs are typically $<2 \times 10^6$ dyn cm$^{-2}$ (see Table 3). Our calculations show that the turbulent pressure in UCHs is larger than the thermal pressure.

The total gas pressure in the PDR is given by

$$P_{\text{PDR}} = knHT_{\text{PDR}} + \frac{n_Hm_H}{C_2^2}v_{\text{C-turb}}^2 \text{ dyn cm}^{-2},$$

(4)

where $v_{\text{C-turb}}$ is the turbulent velocity in centimeters per second estimated from the FWHM of the observed carbon RLs after removing the thermal line width. To estimate PDR pressure we consider that in the region where carbon is ionized, the neutral material is predominantly in atomic hydrogen form (see Hollenbach & Tielens 1997). The estimated total gas pressure in the PDR is typically $10^6$ dyn cm$^{-2}$ (see Table 4). As in the case of the UCH, the turbulent pressure in the PDR is larger than the thermal pressure. This importance of turbulent pressure was previously noted by Xie et al. (1996).

4.2. Robustness of the PDR Parameters and Pressure Estimates

For modeling the PDR properties, we have used the carbon line parameters obtained from our survey. However, as discussed

| $T_{\text{PDR}}$ (K) | $S_L$ (mJy) | $n_{\text{H}}^{\text{PDR}}$ (cm$^{-3}$) | $l$ ($\times 10^3$ pc) | $n_H$ ($\times 10^6$ cm$^{-3}$) | $m_He/n_{\text{H}}$ | $P_{\text{PDR}}$ ($\times 10^5$ dyn cm$^{-2}$) | $P_{\text{PDR}}/P_{\text{0 PDR}}$ |
|---------------------|----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 300                 | 13.0$^b$ | 300              | 2.6             | 1.0             | 0.6             | 1.3             | 0.6             |
|                     | 19.4$^c$ | 1000             | 0.6             | 3.4             | 2.0             | 4.4             | 2.0             |
| 500                 | 13.0$^b$ | 400              | 3.6             | 1.3             | 0.4             | 1.8             | 0.4             |
|                     | 19.4$^c$ | 2000             | 0.5             | 6.7             | 2.0             | 8.9             | 2.0             |

Note.—The electron density, neutral density, and PDR pressure are lower limits.

$^a$ Ratio of the neutral density and PDR pressure estimated with $\pm 20\%$ change in carbon line flux density near 8.5 GHz to those obtained using the line flux density given in Table 2.

$^b$ Carbon line flux density near 8.5 GHz reduced by 20% of that given in Table 2.

$^c$ Carbon line flux density near 8.5 GHz increased by 20% of that given in Table 2.
in § 2, the line flux densities are uncertain by up to 20%. To study the effect of this uncertainty, we estimated the physical properties of the PDR by changing the line flux density near 8.5 GHz by ±20% and compared them with the values given in Table 4. We found that the estimated neutral densities and PDR thickness change by factors of about 2 and 3, respectively. Figure 5 shows the result of such a study toward G32.80+0.19. The PDR parameters and pressures obtained in this study are given in Table 5. We conclude that the lower limits on neutral densities and pressure of the PDR given in Table 4 will decrease only by about a factor of 2 because of the measurement uncertainty of the carbon RL flux density at 8.5 GHz.

5. DISCUSSION

A survey of recombination lines near 8.5 GHz toward 17 UCHs using the Arecibo telescope detected carbon lines from 11 sources (65% detection rate). In this paper, we have shown that the carbon RLs provide important, complementary information on the kinematics and properties of the ambient medium near UCHs. The RLs were used to study the relative motion between the carbon line-forming region and the UCHs. We obtained an rms velocity difference of 3.3 km s\(^{-1}\). Earlier, Forster et al. (1990) compared hydrogen RL and molecular line velocities toward nine compact H\(\Pi\) regions to study their relative motion. They concluded that the RL velocities are offset with respect to molecular lines by typically ±6 km s\(^{-1}\). The relative velocity difference obtained from our observations is about a factor of 2 smaller than that measured by Forster et al. (1990). These authors argue that the larger velocity difference they have measured is consistent with the expansion of a 10\(^4\) K H\(\Pi\) region at the sound speed of ~15 km s\(^{-1}\). The lower velocity difference seen in our observations may indicate that UCHs are not expanding at sound speeds in ionized gas.

The dynamical lifetime for UCHs of a few times 10\(^3\) yr was estimated assuming that the H\(\Pi\) region is expanding at the speed of sound in the ionized gas. However, the lifetime deduced from the observed number of UCHs is a few times 10\(^5\) yr. This discrepancy between the two lifetimes is referred to as the “lifetime problem” of UCHs (Wood & Churchwell 1989a). Several hypotheses have been proposed to explain the long lifetime of UCHs (see Churchwell 1999). For example, De Pree et al. (1995) suggested that if high-density (~10\(^7\) cm\(^{-3}\)), warm (~100 K) molecular material is present in the vicinity of UCHs, it may be able to pressure-confine UCHs that form there and thus extend their lifetime. This hypothesis is supported by recent molecular line observations (e.g., Kurtz et al. 2000), which show that the temperature and density of the molecular clouds harboring UCHs are >50 K and ~10\(^7\) cm\(^{-3}\), respectively. Modeling of carbon RL data in our observations also indicates that UCHs are embedded in neutral regions with high ambient pressure.

In the pressure-confined nebula scenario, if the massive star is stationary with respect to the molecular core, then no relative motion between the ionized gas and the PDR is expected. However, our carbon line observations indicate a nonzero relative motion between the PDR and the ionized gas (see § 3.1). If the star is moving with respect to the cloud core, such relative motion is expected even though the ionized gas is pressure confined. The star motion can also produce the different observed morphologies of UCHs (García-Segura & Franco 2004). However, relative motion between the PDR and ionized gas is expected in other models proposed to solve the long lifetime of UCHs and their morphology. For example, in the model proposed by Kim & Koo (2001), the ionizing star is at the edge of a dense, hot core and the “champagne flow” through the hierarchical structure of the molecular cloud produces the extended emission that has been observed around UCHs. The PDR, in this model, resides in the dense, hot core. The presence of the champagne flow can shift the centroid of the RL emission from the ionized gas relative to the line emission from the PDR. This shift results in a velocity difference between the hydrogen and carbon RLs from the UCHs in our observations. Higher angular resolution observations of carbon RLs may provide enough information to distinguish between these models.

Interestingly, the PDR pressure we derive, in most cases, is an order of magnitude larger than the total pressure in UCHs. In the classical treatment of the pressure-driven evolution of UCHs, a dense shell of neutral material is formed surrounding the H\(\alpha\) region (García-Segura & Franco 1996). If the PDR responsible for the carbon line emission resides in this neutral shell, then its pressure can be high. However, if the ionization front is trapped within the neutral material for ~10\(^5\) yr, then the sound crossing length scale (~0.2 pc; sound speed ~2 km s\(^{-1}\)) is larger than the typical molecular cloud core sizes (~0.1 pc; Churchwell 2002). Thus, the neutral shell would have diffused out in a fraction of the expected lifetime of the UCHs, and hence the ambient pressure outside the UCH is most likely that of the natal molecular cloud. The large pressure difference, therefore, may indicate that the dominant pressure inside the UCH is due to other physical processes such as stellar wind. Further investigation with high angular resolution, multifrequency RL and continuum observations, together with modeling of the evolution of H\(\alpha\) regions surrounded by a dense PDR, is needed to understand this large pressure difference.

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