MAGNETIC FIELDS AT THE PERIPHERY OF ULTRACOMPACT H II REGIONS
FROM CARBON RECOMBINATION LINE OBSERVATIONS

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ABSTRACT

Several indirect evidences indicate a magnetic origin for the nonthermal width of spectral lines observed toward molecular clouds. In this Letter, I suggest that the origin of the nonthermal width of carbon recombination lines (CRLs) observed from photodissociation regions (PDRs) near ultracompact H II regions is magnetic and that the magnitude of the line width is an estimate of the Alfvén speed. The magnetic field strengths estimated based on this suggestion compare well with those measured toward molecular clouds with densities similar to PDR densities. I conclude that multifrequency CRL observations have the potential to form a new tool to determine the field strength near star-forming regions.

Subject headings: H II regions — ISM: lines and bands — ISM: magnetic fields — ISM: molecules — MHD — radio lines: ISM

1. INTRODUCTION

Observations of high-density molecular line tracers toward ultracompact H II regions (UCHs) reveal that these H II regions are embedded in dense ($\gtrsim 10^3$ cm$^{-3}$) molecular clouds (e.g., Churchwell et al. 1990; Churchwell 2002 and references therein). Far-ultraviolet (6–13.6 eV) radiation from massive stars within the UCHs heats the dense molecular material in this interface, producing a photodissociation region (PDR; see Hollenbach & Tielens 1997). Carbon recombination lines (CRLs) from such regions have been detected toward a large number of UCHs, establishing the presence of dense PDRs near most UCHs (Roshi et al. 2005b).

The observed width of the CRLs from PDRs associated with UCHs is typically between 4 and 8 km s$^{-1}$. The gas temperature in the PDR, obtained by non-LTE modeling of CRL emission at multiple frequencies, is in the range 200–1000 K (Roshi et al. 2005a; Garay et al. 1998; Natta et al. 1994). Thus, the expected thermal contribution to the line width is at least a factor of 2 smaller than the observed width (see Fig. 1). This larger observed width indicates that the CRL width is dominated by supersonic motions. In fact, a similar situation exists in molecular clouds. It has long been recognized that the observed width of spectral lines from molecular clouds have a nonthermal component and this component is often supersonic (e.g., Barrett et al. 1964). The origin of the nonthermal component of the line width is now attributed to either “turbulence” (Morris et al. 1974; Zuckerman & Evans 1974) or Alfvén waves (Arons & Max 1975; Mouschovias 1975; see also Shu et al. 1987 and references therein).

Detailed theoretical models for both turbulence and Alfvén waves in molecular clouds are yet to be worked out. But turbulence without any magnetic field is a less plausible proposition since observations demand supersonic turbulence and the rapid dissipation in shocks cannot sustain such turbulent motions to timescales larger than the free-fall time (e.g., Shu et al. 1987). The decay of Alfvén waves are slow compared to supersonic turbulence although simulations show that they may also need a driving mechanism (Mac Low 2003). Thus, Alfvén waves appear to be a more tenable explanation for the observed line widths (Arions & Max 1975; Mouschovias 1975).

Observational data also seem to indirectly support the magnetic origin of the line width. Analysis of the width of spectral lines observed toward molecular clouds shows power-law relationships between the nonthermal component of the velocity dispersion, the cloud size, density, and the magnetic field strength (Larson 1981; Troland & Heiles 1986; Myers & Goodman 1988a, 1988b; Mouschovias & Psaltis 1995; Crutcher 1999). These relationships are expected in self-gravitating, magnetically supported clouds since the Alfvén waves in such clouds affect the observed line width (Mouschovias 1987; Myers & Goodman 1988a, 1988b).

In this Letter, I use the observed nonthermal widths of CRLs to estimate the magnetic field strength in PDRs near UCHs. The field strength is estimated by assuming that the nonthermal velocity dispersion of carbon lines gives an estimate of the Alfvén speed in the PDR. This assumption is based on a comparative study of the characteristics exhibited by the CRL and molecular line data. The data and the comparative study are presented in §§ 2 and 3, respectively. The magnetic field strength is obtained by combining the velocity dispersion of CRL and the density derived from modeling carbon line emission (see § 4). To our knowledge the only attempt to compute the magnetic field using CRLs was made by Vallee (1989), where he had applied a model for shocks at the edge of molecular clouds to deduce the field strength.

2. CARBON RECOMBINATION LINE DATA

For the present analysis I use CRL data toward UCHs since the PDR thickness is small in these cases, and therefore large-scale motions (such as outflows) may not affect the line width (see § 5). Table 1 summarizes the CRL data and results obtained from modeling these data toward 14 UCHs. Listed are the source name, observed CRL transition, FWHM of CRLs, PDR gas temperature, carbon ion density, number density of hydrogen atoms in the PDR, line-of-sight extent of the PDR ($L_{\odot}$), and the estimated magnetic field strength (see § 4).

The quality of the CRL data obtained toward all 14 sources is good; the uncertainties are mostly in the parameters derived by modeling line emission. The frequencies of the selected CRLs are below $\sim$15 GHz. As inferred from modeling, carbon

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2 The relationship $\Delta V = [8 \ln (2)]^{1/2} \sigma_{\text{est}}$ is used in this Letter to relate the FWHM line width $\Delta V$ to the dispersion $\sigma_{\text{est}}$ for a Gaussian line model.
The LSR velocity is with respect to the C89 temperature of 1000 K. The large difference between the observed line profiles and the Gaussian curves demonstrates the dominance of nonthermal motions. The Gaussian profiles correspond to an assumed PDR gas temperature of 1000 K. The large difference between the observed line profiles and the Gaussian curves demonstrates the dominance of nonthermal motions in the PDR. The LSR velocity is with respect to the C89 (9.1779 GHz) transition.

line emission is dominated by stimulated emission at these frequencies (Natta et al. 1994; Roshi et al. 2005b). The data toward the first seven sources in Table 1 were obtained using interferometric observations. The line widths for the first six sources were obtained from profiles averaged over regions where lines were detected. The properties of the PDR toward W3A were not well constrained; I have taken representative model parameters from Kantharia et al. (1998). Data toward the remaining seven sources were obtained with the Arecibo telescope. Modeling of CRL emission toward these sources was limited by (1) poor angular resolution, (2) flux density calibration error, and (3) detection of line only near 9 GHz. Thus, modeling this data set has given only constraints on the physical properties of the PDR. The PDR gas temperature of 500 K for the Arecibo sources and W48A, W49G, and W49J listed in Table 1 is a representative value. The carbon ion density and \( L_1 \) obtained from modeling depend nonlinearly on the gas temperature. Converting the ion density to neutral density is somewhat uncertain due to the unknown depletion factor and the fraction of molecular hydrogen in the CRL-forming region. Based on the examination of the models for W48A and our experience in modeling other CRL data set (Roshi et al. 2005a, 2005b, 2006), it is expected that the values for temperature in Table 1 can vary by a factor of 2 and the values for neutral density and \( L_1 \) can vary by a factor of 4. The model parameters are derived using a simplified geometry of plane-parallel PDR slabs. A comparison of the PDR properties obtained from such models toward W48A with those obtained from models that take into account the photo and chemical processes in the PDR shows that detailed modeling gives values within the factors quoted above (S. Jeyakumar et al. 2007, in preparation).

3. ALFVÉN SPEED IN MOLECULAR CLOUDS AND NONTHERMAL WIDTH OF CARBON RECOMBINATION LINES

Molecular clouds are largely neutral with a small admixture of partially ionized heavy elements with their free electrons (ionization fraction \( 10^{-5} \)). Any wave motion of the magnetic fields in molecular clouds is strongly coupled to the ions. For those waves with \( \lambda \ll \lambda_{\text{max}} \), the timescale of momentum transfer between ions and neutrals is smaller than the magnetic perturbation timescale, and hence neutrals are also coupled to such waves (Arons & Max 1975). For typical magnetic fields of \( 1 \text{ mG near } \text{dense} \text{ regions in star-forming clouds and neutral densities of } 10^6 \text{ cm}^{-3} \) (e.g., Johnston et al. 1989), \( \lambda_{\text{max}} \sim 3 \times 10^{-7} \text{ pc} \), which is much smaller than the size of these dense clouds.

| Source Name | Transition | \( \Delta V \) (km s\(^{-1}\)) | \( T_{\text{ion}} \) (K) | \( n_{\text{e}} \) (cm\(^{-3}\)) | \( n_{\text{n}} \) (x 10\(^6\) cm\(^{-3}\)) | \( L_1 \) (x 10\(^{-3}\) pc) | \( B \) (mG) | Reference |
|-------------|------------|-------------------------------|------------------------|------------------|--------------------------|-------------------|--------------|----------|
| W48A        | C7\(\alpha\) | 4.5(0.8)                     | 500                    | 2500             | 8.5                      | 0.3               | 2.9          | 1         |
| W49G        | C9\(\alpha\) | 9.5(0.8)                     | 500                    | 3000             | 10.0                     | 0.1               | 6.8          | 2         |
| W49J        | C9\(\alpha\) | 15.1(1.5)                    | 500                    | 2800             | 9.0                      | 0.4               | 10.4         | 2         |
| S88B-east   | C9\(\alpha\) | 4.4(0.3)                     | 600                    | 80               | 0.4                      | 160.0             | 0.6          | 3         |
| S88B-west   | C9\(\alpha\) | 5.6(0.4)                     | 400                    | 40               | 0.2                      | 220.0             | 0.6          | 3         |
| GDG 12-15   | C9\(\alpha\) | 4.7(0.7)                     | 330                    | ...              | 0.02                     | 130.0             | 0.1          | 4         |
| W3A         | C168\(\alpha\) | 5.5(0.9)                    | 100                    | ...              | 0.1                      | 50                | 0.4          | 5         |
| G32.80+0.19 | C89\(\alpha\) | 7.5(1.3)                     | 500                    | 1000             | 3.4                      | 1.1               | 3.1          | 6         |
| G37.87−0.40 | C89\(\alpha\) | 14.0(1.5)                    | 500                    | 120              | 0.4                      | 29.0              | 2.0          | 6         |
| G43.24−0.05 | C89\(\alpha\) | 6.0(0.9)                     | 500                    | 300              | 1.0                      | 9.0               | 1.4          | 6         |
| G45.12+0.13 | C89\(\alpha\) | 12.9(1.9)                    | 500                    | 40               | 0.1                      | 124.0             | 0.9          | 6         |
| G45.45+0.0  | C89\(\alpha\) | 9.6(2.9)                     | 500                    | 30               | 0.1                      | 150.0             | 0.7          | 6         |
| G70.29+1.6  | C89\(\alpha\) | 8.3(0.5)                     | 500                    | 350              | 1.2                      | 8.6               | 2.1          | 6         |
| G70.33+1.59 | C89\(\alpha\) | 4.2(0.4)                     | 500                    | 170              | 0.6                      | 25.0              | 0.7          | 6         |

\(^{a}\) Modeling of carbon line emission for these sources has provided upper limits for \( n_{\text{e}} \) and \( n_{\text{n}} \) and lower limits for \( L_1 \).

\(^{b}\) The data for these sources are taken from the Arecibo survey. Modeling of carbon line emission for these sources has provided lower limits for \( n_{\text{e}} \) and \( n_{\text{n}} \) and upper limits for \( L_1 \).

REFERENCES.— (1) Roshi et al. 2005b; (2) Roshi et al. 2006; (3) Garay et al. 1998; (4) Gomez et al. 1998; (5) Kantharia et al. 1998; (6) Roshi et al. 2005a.
regions (fraction of a parsec). Thus, magnetic waves with \( \lambda \approx 3 \times 10^{-7} \) pc can exist in dense regions, and the characteristic speed (Alfvén speed) of these waves is determined by the total density (i.e., ion + neutral density) of the molecular cloud (Arons & Max 1975).

Crutcher (1999) compiled the available sensitive Zeeman measurements of magnetic field strengths in molecular clouds and their neutral densities. Using these data, I estimate the Alfvén speed \( V_A \) (units of cm s\(^{-1}\)) in these clouds;

\[
V_A = \frac{2B_{\text{los}}}{4\pi\mu n_n m_H},
\]

where \( n_n \) is the hydrogen atom density in units of cm\(^{-3}\), \( \mu = 1.4 \) is the effective mass of an H+He gas with cosmic abundance, and \( m_H \) is the mass of the hydrogen atom in grams. The measured line-of-sight magnetic field, \( B_{\text{los}} \), in units of gauss, is multiplied by 2 to convert it into total field strength (Crutcher 1999). Figure 2 shows the estimated Alfvén speed in the molecular cloud sample taken from Crutcher (1999). The estimated Alfvén speeds are confined to a narrow range between 0.7 and 4 km s\(^{-1}\) with a median value of 1.6 km s\(^{-1}\). This “constancy” of Alfvén speed was noted earlier and has been understood from models of magnetic confinement of molecular clouds (e.g., Mouschovias & Psaltis 1995; Basu 2000).

We now compare the nonthermal velocity dispersion of carbon lines, \( \sigma_{\text{nt}} \), observed from PDRs with Alfvén speed in molecular clouds. The nonthermal width is obtained by removing the thermal contribution, estimated using the gas temperature \( T_{\text{gas}} \) (see Table 1), from the observed CRL width. The nonthermal line widths are plotted in Figure 2 for the corresponding PDR densities inferred from carbon line modeling. The nonthermal widths have values between 1.6 and 6 km s\(^{-1}\) with a median value of 2.9 km s\(^{-1}\). Figure 2 shows that the nonthermal line widths are almost constant over 3 orders of magnitude in density. The constancy of the nonthermal line widths and their magnitudes are similar (less than a factor of 2) to those inferred for Alfvén waves in molecular clouds.

The gas phase carbon is ionized in PDR and hence is strongly coupled to the magnetic field in these regions. If we consider similar physical parameters in PDRs as in dense molecular regions (\( n_n \sim 10^4 \) cm\(^{-3}\); \( B \sim 1 \) mG), then \( \lambda_{\text{min}} \sim 3 \times 10^{-7} \) pc is at least 2 orders of magnitude smaller than the typical line-of-sight thickness of the PDR (i.e., \( L_\alpha \)). Thus, Alfvén waves with \( \lambda \geq \lambda_{\text{min}} \) exist in the PDR, and here I consider their contribution to the nonthermal width of the observed carbon lines. The amplitude of the velocity of carbon ions, \( \delta v \), due to these waves is related to the magnetic perturbation amplitude \( \delta B \) through the equation (e.g., Arons & Max 1975)

\[
\delta v = \frac{\delta B}{\sqrt{4\pi\mu n_n m_H}}.
\]

The observed nonthermal velocity dispersion is approximately given by \( \delta v \). It is usually assumed that \( \delta B \sim B \); in that case, the right-hand side of equation (2) becomes identical to that of equation (1). Based on these considerations and the characteristics exhibited by the nonthermal velocity dispersion and Alfvén speed in molecular clouds (see above), we assume that the velocity dispersion of carbon lines is an estimate of the Alfvén speed in the PDR.

The observed velocity dispersion is usually scaled by \( \sqrt{3} \) to convert it to three-dimensional (3D) velocity dispersion. This scaling assumes random magnetic field orientation along line-of-sight and random polarization of Alfvén waves. Carbon lines are observed from PDRs near UCHs where shocks are present. In such shocked regions only the tangential component of the magnetic field is amplified, and the Alfvén speed associated with this component is scaled by the square root of the density compression ratio (McKee & Zweibel 1995). Hence, the scaling factor needed to convert the observed velocity dispersion to a 3D dispersion is uncertain. Direct observation of the Zeeman effect of CRLs may help in determining this factor (see § 5). Here I note a systematically high value (a factor of 1.8) for the CRL velocity dispersion compared to the Alfvén speed in molecular clouds, which may be an indication of higher Alfvén speeds in PDR shocks.

4. MAGNETIC FIELD IN PHOTODISSOCIATION REGIONS

The magnetic field strength is obtained using equation (1) by substituting the estimated nonthermal velocity dispersion of CRL for the Alfvén speed and using the neutral density obtained from modeling the CRL emission (e.g., Roshi et al. 2005a). Field strength values thus obtained are tabulated in Table 1. These values represent the total magnetic field strength in the PDR. Based on the expected range of the derived physical properties of the PDR (see § 2), the estimated uncertainty in \( B \) is typically a factor of 2.5.

In Figure 3, we compare the estimated magnetic field with those measured toward molecular clouds. The ordinate of the plot is the number density of H\(_2\) molecules. Here the estimated field strength values in the PDR are compared with those measured in molecular clouds with similar density. Such a comparison is possible since earlier observations toward molecular clouds show that the magnetic field scales with density \( (n_{\text{H}_2} \propto \rho^{0.47}; \text{Crutcher 1999}) \). To produce Figure 3, the neutral density of the PDR given in Table 1 is divided by 2 to convert it into the number density of H\(_2\). As seen in the figure, the estimated magnetic field strengths in the PDR compare well
within errors with those measured toward molecular clouds with similar density.

Magnetic field measurements using the Zeeman effect of CRLs near 1.4 GHz were attempted toward a few H II regions (Silvergate 1984) of which W48 and S88B are of interest here. The 1.4 GHz CRL emission toward W48 does not originate from the PDR associated with the UCH (Roshi et al. 2005a), and hence a comparison of the upper limit on the field strength obtained by Silvergate (1984) with the estimated value here is not meaningful. Toward S88B, the upper limit for the magnetic field strength in the range of 0.1–0.3 mG was obtained by magnetic effects are available in literature toward a few of the UCHs listed in Table 1. Magnetic field measurements using OH or H I Zeeman effects are available in literature toward a few of the UCHs listed in Table 1. I compare the field strength obtained in Table 1 with the results of these observations. Note that OH and H I lines may originate from different spatial locations compared to the CRL-forming region. From OH Zeeman observations toward S88B a field strength in the range 0.1–0.3 mG was obtained by 

5. DISCUSSION

As mentioned in § 2, CRL emission is dominated by stimulated emission for the transitions listed in Table 1. Because of the dominance of stimulated emission, the carbon line is detected only from the near side of the UCH. The nondetection from the far side of the UCH means that the width of the CRL is not contributed to by the expansion of the UCH (if the UCH were expanding). Thus, the line width has contribution only from thermal and nonthermal motions. The carbon line width may also have contributions from large-scale motions such as outflows. However, the similarity of line widths observed from different sources (see Table 1) may indicate that this contribution is small. Thus, the field strength estimated in § 4 may not be affected by such large-scale motions. However, presence of any nonmagnetic turbulence would affect the estimation of the field strength, and hence the values obtained should be considered as upper limits.

The magnetic origin of CRL width can be confirmed by measuring the field strength using Zeeman effect of carbon lines from the PDRs and comparing it with the values estimated in § 4. If confirmed, then multifrequency CRL observations form another tool to deduce the strength of magnetic fields near star-forming regions.

Note added in manuscript.—After this Letter was accepted, through Professor Ferland I was made aware of discussions in papers (Ferland 2001; Beckman & Monica 2004) regarding the magnetic contribution to the width of spectral lines from H II regions.

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REFERENCES

Arons, J., & Max, C. E. 1975, ApJ, 196, L77
Barrett, A. H., Meeks, M. L., & Weinreb, S. 1964, Nature, 202, 475
Basu, S. 2000, ApJ, 540, L103
Beckman, J. E., & Relano, M. 2004, Ap&SS, 292, 111
Brogan, C. L., & Troland, T. H. 2001, ApJ, 550, 799
Churchwell, E. 2002, ARA&A, 40, 27
Churchwell, E., Walmsley, C. M., & Cesaroni, R. 1990, A&AS, 83, 119
Crutcher, R. M. 1999, ApJ, 520, 706
Ferland, G. 2001, PASP, 113, 41
Garay, G., Lizano, S., Gomez, V., & Brown, R. L. 1998, ApJ, 501, 699
Gomez, V., et al. 1998, ApJ, 503, 297
Hollenbach, D. J., & Tielens, A. G. G. M. 1997, ARA&A, 35, 179
Johnston, K. J., Migenes, V., & Norris, R. P. 1989, ApJ, 341, 847
Kantharia, N. G., Anantharamaiah, K. R., & Goss, W. M. 1998, ApJ, 504, 375
Larson, R. B. 1981, MNRAS, 194, 809
Mac Low, M.-M. 2003, in Simulations of Magnetohydrodynamic Turbulence in Astrophysics, ed. T. Passot & E. Falgarone (Berlin: Springer), 182
McKee, C. F., & Zweibel, E. G. 1995, ApJ, 440, 686
Morris, M., Zuckerman, B., Turner, B. E., & Palmer, P. 1974, ApJ, 192, L27
Mouschovias, T. Ch. 1975, Ph.D. thesis, Univ. California, Berkeley
———. 1987, in Physical Processes in Interstellar Clouds, ed. G. E. Morfill & M. Scholer (Dordrecht: Reidel), 453
Mouschovias, T. Ch., & Psaltis, D. 1995, ApJ, 444, L105
Myers, P. C., & Goodman, A. A. 1988a, ApJ, 326, L27
———. 1988b, ApJ, 329, 392
Natta, A., Walmsley, C. M., & Tielens, A. G. G. M. 1994, ApJ, 428, 209
Roshi, D. A., Balser, D. S., Bania, T. M., Goss, W. M., & De Pree, C. G. 2005a, ApJ, 625, 181
Roshi, D. A., De Pree, C. G., Goss, W. M., Anantharamaiah, K. R. 2006, ApJ, 644, 279
Roshi, D. A., Goss, M. W., Anantharamaiah, K. R., & Jeyakumar, S. 2005b, ApJ, 626, 253
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Silverplate, P. R. 1984, ApJ, 279, 694
Troland, T. H., & Heiles, C. 1986, ApJ, 301, 339
Vallee, J. P. 1989, A&A, 224, 191
van der Werf, P. P., & Goss, W. M. 1990, A&A, 238, 296
Zuckerman, B., Evans, N. J., II, 1974, ApJ, 192, L149

A. P. Sarma et al. (2007, in preparation) consistent with our estimate. Van der Werf & Goss (1990) using H I Zeeman observations measured a peak magnetic field of 0.1 mG in the −45 km s\(^{-1}\) component observed toward W3. The CRL LSR velocity is comparable with this velocity, and the field strength is consistent with the estimated value. Brogan & Troland (2001) measured a maximum field strength of 0.3 mG toward W49A. They used the Zeeman effect of H I to measure the field strength with an angular resolution of 25°. The measured value is about 20 times smaller than the estimated value, possibly because the two tracers (H I and CRL) do not probe the same region in this case.