INTERNAL DYNAMICS OF THE HYPERCOMPACT H II REGION G28.20−0.04N

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ABSTRACT

High-resolution (0.15") Very Large Array observations of 7 mm continuum and H53α line emission toward the hypercompact H II region G28.20-0.04N reveal the presence of large-scale ordered motions. We find a velocity gradient of 10^3 km s^{-1} pc^{-1} along the minor axis of the continuum source. Lower resolution (1.0"–2.3") radio recombination line observations indicate a systematic increase of line width from H30α to H92α. Under the assumption that the H30α line does not suffer significant pressure broadening, we have deconvolved the contributions of statistical broadening (thermal, turbulent, and pressure) from large-scale motions. The pressure broadening of the H53α, H76α, and H92α lines implies an electron density of 7 × 10^5, 9 × 10^5, and 3 × 10^5 cm^{-3}, respectively.

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

1. INTRODUCTION

Hypercompact (HC) H II regions have about one-tenth the size (<0.05 pc) and about 100 times the density (n_e > 10^5 cm^{-3}) of ultracompact (UC) H II regions. It has been postulated that HCHs represent the transition from hot molecular cores to UCHII regions (Kurtz 2000); that is, the transition from rapid accretion onto a massive central protostar to the termination of ultracompact (UC) H II regions. Hypercompact regions (Kurtz 2000); that is, the transition from rapid accretion onto a massive central protostar to the termination of bipolar outflows, rotation, and shocks due to accretion and outflows. Also, owing to their high electron densities, recombination lines from the H II gas should suffer substantial pressure broadening in high quantum state radio recombination lines (RRLs).

It is not clear if HCHII regions are simply smaller and denser versions of UCHII regions or if they are intrinsically different. Their relative sizes, however, suggest that stellar clusters may be responsible for UCHII regions, while HCHII regions may be produced by a single, or perhaps a binary, OB protostar. Some, but not all, HCHII regions have unusually broad radio recombination lines (BRRls), with full widths at half maximum intensity (FWHM) >40 km s^{-1}. The typical FWHM of more evolved (UC and compact) H II regions is ~25–30 km s^{-1} in all RRLs from principal quantum states n < 100. The fact that not all HCHII regions have BRRls may imply that BRRls are only present for a limited period during the earliest HCHII evolutionary phase, when ordered large-scale motions are maximum.

Sewiło et al. (2004, and in preparation) observed the H92α, H76α, and H53α lines toward the HCH region G28.20-0.04N (hereafter G28.20N) with resolutions of 2.3", 1.5", and 1.6", respectively, all of which are larger than the angular size of the HCH region. They found FWHMs of 74 km s^{-1}, 58 km s^{-1}, and 40 km s^{-1}, respectively. The rapid change in line width with transition strongly suggests that pressure broadening is a dominant broadening mechanism in G28.20N.

We have chosen G28.20N for a high-resolution H53α study to determine the origin of the BRRls in this source because it is a bona fide HCHII region, it has already been observed in several RRLs at lower angular resolution, and several masers have been detected toward G28.20N, implying extreme youth (H2O, Han et al. 1998; OH 6035 MHz, Caswell & Vaile 1995; OH 1667 MHz, Argon et al. 2000; CH3OH, Menten 1991). The H53α line was chosen because it should be mostly free from pressure broadening, the nebula should be optically thin at this frequency, and the Very Large Array can achieve an angular resolution one-tenth that of previous observations at 43 GHz.

2. OBSERVATIONS

G28.20N was observed with the VLA6 at 7 mm (continuum and H53α line) with an angular resolution of 0.15". The observations were made on 2004 January 19 with the VLA in its B-configuration. At the H53α rest frequency of 42.95197 GHz, this provided an angular resolution of 0.17" × 0.13" at a position angle of ~4.8°. A 25 MHz bandwidth was employed, with 31 spectral line channels of 781 kHz each. This provided a velocity resolution of 5.5 km s^{-1}, which was later Hanning smoothed to 11 km s^{-1}. Integration time on-source was about 1.4 hr. 3C 286 (1.47 Jy), 1851+005 (0.68 ± 0.01 Jy), and 3C 345 (4.81 ± 0.18 Jy) were used as flux density, phase, and bandpass calibrators, respectively. The data reduction, including self-calibration, followed the VLA high-frequency guidelines for calibration and imaging, using the NRAO package AIPS. The continuum image is shown in Figure 1. Continuum-subtracted line images were used to generate H53α maps.

3. RESULTS

3.1. Morphology of the Source

At high angular resolution, G28.20N appears as a shell-like structure, extended in the SE-NW direction (Fig. 1). There are two peaks, separated by 0.36" (2050 AU or 0.01 pc at a distance of 5.7 kpc; Fish et al. 2003). The brightness distributions

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Footnotes:

6 The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory (NRAO), a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
The velocity structure observed in G28.20N is consistent with a torus rotating with a velocity of 5.0 km s\(^{-1}\) at a radius of 0.005 pc (1030 AU; at the position of the peaks), which corresponds to a velocity gradient of about 10\(^3\) km s\(^{-1}\) pc\(^{-1}\), or an interior mass of 28 \(M_\odot\) for Keplerian motion.

### 3.3. Optical Depth Effects

We compared integrated line profiles for all transitions and found that the H30\(\alpha\) line velocity shifts by about 5–14 km s\(^{-1}\) with respect to the H92\(\alpha\), H76\(\alpha\), and H53\(\alpha\) lines. The H92\(\alpha\), H76\(\alpha\), and H53\(\alpha\) line velocity integrated over the nebula is 82.9 ± 0.9, 78.9 ± 0.8, and 88.2 ± 0.4 km s\(^{-1}\), respectively. Keto et al. (2008) reports the H30\(\alpha\) line velocity of 92.5 ± 0.2 km s\(^{-1}\).

A similar trend of increasing RRL velocity with increasing frequency has been reported for other compact H\(\alpha\) regions, e.g., W49A/B (De Pree et al. 1997) and W3(OH) (Berulis & Ershov 1983). Welch & Marr (1987) and Keto et al. (1995) proposed that this is an optical depth effect, in which deeper layers with different velocities are probed at higher frequencies. Following their arguments, the optical depth decreases rapidly at high frequencies because the absorption coefficient is inversely proportional to the square of the frequency; thus the H92\(\alpha\), H76\(\alpha\), H53\(\alpha\), and H30\(\alpha\) emission arise from different volumes of gas, with H30\(\alpha\) emission being more sensitive to the denser regions. They also argue that the velocity of the high-frequency RRLs provides a good approximation to the average motion of the H\(\alpha\) region provided that the random motions are the same for all densities throughout the nebula. The velocity of this innermost H\(\alpha\) gas is expected to most closely indicate the stellar velocity; hence, for G28.20N, the H30\(\alpha\) line velocity should provide the best estimate of the central star’s radial velocity. The blueshifted density and, \(S_L/S_C\) and \(\int S_L/S_C\ dv\) are the line-to-continuum ratios at line center and integrated over the line profile, respectively. The continuum flux densities in Table 1 are determined by integrating over the same areas of the source used to generate the line profiles. In some directions (e.g., E and H) the line profiles are asymmetric, with an additional velocity component apparent. All the asymmetries occur in the velocity range of ~110–130 km s\(^{-1}\). Although weak, these features are real; we also detect a 130 km s\(^{-1}\) component in the H76\(\alpha\) line.

The sequence of five H53\(\alpha\) line profiles shown in Figure 2 indicates a systematic shift in the central line velocity from the NE to SW. The dotted vertical line indicates the 88.2 km s\(^{-1}\) systemic velocity of the nebula obtained from H53\(\alpha\) data taken with 10 times lower resolution than shown in boxes A–E (upper right; HPBW ~ 1.6\(^\circ\)). Thus, the centroid velocity of ~78 km s\(^{-1}\) in box A (NE side of G28.20N) is blueshifted and the centroid velocity of ~97 km s\(^{-1}\) in box E (SW side of G28.20N) is redshifted with respect to the systemic nebular velocity. The H53\(\alpha\) lines suggest rotational motion, with the axis of rotation in the SE–NW direction. There is no velocity pattern along the elongated SE–NW axis (i.e., no indication of an outflow along this axis). We suggest that the excess line broadening along this axis may be due to an outflow in the plane of the sky, expanding perpendicular to its axis of flow with a velocity of ~5 km s\(^{-1}\).

Figure 1.—7 mm image of G28.20–0.04 N. The continuum intensity peak is 64.0 mJy beam\(^{-1}\). The contours are –3, 3, 6, 9, 12, 20, 30, 50, 70, 90, 110 × 0.53 mJy beam\(^{-1}\) (the image rms). The synthesized beam of 0.17\('\) × 0.13\('\) is shown in the lower left corner. The insets show intensity cuts through G28.20N; position angles indicate rotation east from north.

We examined the velocity structure of G28.20 by making contour plots of the H53\(\alpha\) emission, using moment maps, position–velocity diagrams, and Gaussian fitting of the line profiles at multiple positions. All these methods reveal a velocity gradient of ~130 km s\(^{-1}\) along one-dimensional cuts through the source show a well-defined shell with low intensity at the center. The center of the shell-like nebula is at R.A. = 18\(^{h}\)42\(^{m}\)58.11\(^{s}\) and decl. = –04\('\)13\('\)57.4\('\) (J2000). The source diameter at 10% of the peak (the 12 \(\sigma\) contour in Fig. 1) is \(\theta_c = 0.9\('\) [5100 AU, where \(\theta_c = (\theta_{RA} \cdot \theta_{decl})^{1/2}\)]. The integrated flux density is 645 ± 65 mJy, where the 10% uncertainty reflects VLA calibration uncertainty in the 7 mm band. The synthesized beam brightness temperature using the peak brightness of 64 mJy beam\(^{-1}\) (located at the west side of the shell) is 1920 K, implying a peak optical depth of 0.3 based on \(T_e = 7000\) K, and a peak emission measure (EM) of 1.6 × 10\(^6\) pc cm\(^{-6}\). This EM implies an rms electron density \((n_{e\,rms})\) of 6.2 × 10\(^5\) cm\(^{-3}\). The synthesized beam brightness temperature of the central cavity, 11 mJy beam\(^{-1}\), corresponds to 340 K, implying an optical depth of 0.05, an EM of 2.5 × 10\(^6\) pc cm\(^{-6}\), and an \(n_{e\,rms}\) of 2.5 × 10\(^5\) cm\(^{-3}\).

### 3.2. Velocity Structure

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\[ \frac{d}{dt} \frac{dS}{d\nu} = \int \left( \frac{dS}{d\nu} - S \right) \frac{d\nu}{dt} \, dv \]

Our 7 mm flux density and H53\(\alpha\) line width (both B- and D-array) disagree with the results of Keto et al. (2008) for their 7 mm/H53\(\alpha\) data (S\(_\text{int} = 1.1\) Jy and FWHM = 33.4 ± 1.5 km s\(^{-1}\)). To investigate this discrepancy, we re-reduced our lower resolution 7 mm data and the archival Keto et al. data (AK607) using consistent procedures for both data sets. We confirmed our results and found that the Keto et al. data are consistent with our own. For the AK607 data we find an integrated 7 mm continuum flux density of 790 ± 35 mJy and a FWHM for the H53\(\alpha\) line of 38.7 ± 0.9 km s\(^{-1}\).
velocities of the outer H II region, traced by the H92α, H76α, and H53α lines, imply expansion, consistent with a strongly overpressured nebula.

4. LINE BROADENING MECHANISMS: PRESSURE BROADENING VS. DYNAMIC MOTIONS

Keto et al. (2008) detected the H30α line toward G28.20N using the SMA with an angular resolution of 1″. The width of the H30α line is 20.9 ± 0.6 km s⁻¹. At the high frequency of the H30α line, line width should be dominated by the thermal, turbulent, and large-scale motions; pressure broadening is negligible due to the rapid decrease in pressure broadening with frequency. Thermal and turbulent broadening produce convolved Gaussian profiles whose center velocities generally coincide. Large-scale coherent motions can produce velocity-shifted profiles that may deviate from Gaussian shapes. The observed profiles depend on the type and angular extent of the large-scale velocity components relative to the synthesized beam. In particular, as the angular resolution is increased, each resolution element should approach the combined thermal plus turbulent broadening of the gas, with its central velocity reflecting the dominant large-scale motion of the gas in that volume element. In some cases, two components of large-scale coherent motions may fall within a single beam, which may result in a double...
Gaussian. An example of this is an expanding bubble whose front and back faces are included in all observations or if the red and blue lobes of an outflow are projected onto the same resolution element.

Molecular line observations of UCHII regions and massive cloud cores suggest that the typical molecular line width where HCHII regions form is ~5 km s$^{-1}$ (FWHM; Cesaroni et al. 1991; Plume et al. 1997). We adopt this value for the nonthermal HCH line widths. The nonthermal line widths are derived from Gaussian fits to the high resolution H53 line data. The Gaussian width is 2.99 MHz and the observed line width is 5.69 MHz, implying a pressure-broadening width of 4.03 MHz (or 8.1 km s$^{-1}$). For the H76$\alpha$ line, the Gaussian width is 1.02 MHz and the observed line width is 2.82 MHz, implying a pressure-broadening width of 4.2 MHz (or 9.5 km s$^{-1}$).

### Table 1

| Box       | $V_{\text{LSR}}$ (km s$^{-1}$) | FWHM$_{\text{deconv}}$ (km s$^{-1}$) | $S_e$ (mJy) | $S_C$ (mJy) | $S_e/S_C$ (peak) | $f S_e/S_C$ de (km s$^{-1}$) |
|-----------|-------------------------------|-------------------------------------|------------|------------|-----------------|----------------------------|
| A.......... | 77.6 ± 1.7                    | 3.49 ± 4.9                          | 5.1 ± 1.0  | 12.1 ± 0.6 | 0.42 ± 0.08     | 16.3 ± 2.4                 |
| B.......... | 85.8 ± 0.5                    | 3.38 ± 1.3                          | 22.5 ± 1.1 | 53.4 ± 0.6 | 0.42 ± 0.02     | 16.0 ± 0.6                 |
| C.......... | 92.1 ± 0.7                    | 3.59 ± 2.2                          | 6.7 ± 0.6  | 23.2 ± 0.6 | 0.29 ± 0.03     | 11.6 ± 0.8                 |
| D.......... | 95.8 ± 0.4                    | 3.16 ± 1.0                          | 26.4 ± 1.1 | 66.5 ± 0.6 | 0.40 ± 0.02     | 14.2 ± 0.4                 |
| E$^*$      | 97.3 ± 1.0                    | 2.89 ± 3.0                          | 7.8 ± 1.0  | 17.9 ± 0.6 | 0.44 ± 0.06     | 14.4 ± 1.3                 |
| F.......... | 127.9 ± 3.0                   | 9.4 ± 5.0                           | 1.8 ± 1.3  | ...        | 0.10 ± 0.07     | 1.5 ± 0.8                  |
| G.......... | 89.9 ± 1.3                    | 29.6 ± 3.7                          | 4.0 ± 0.7  | 10.4 ± 0.6 | 0.39 ± 0.07     | 13.0 ± 1.7                 |
| H$^*$      | 87.7 ± 0.8                    | 36.6 ± 2.4                          | 11.4 ± 1.0 | 29.5 ± 0.6 | 0.39 ± 0.04     | 15.8 ± 1.1                 |
| I.......... | 82.8 ± 1.7                    | 26.5 ± 3.3                          | 10.1 ± 1.7 | 34.7 ± 0.6 | 0.29 ± 0.05     | 8.9 ± 1.1                  |
| J.......... | 110.3 ± 4.0                   | 21.1 ± 7.4                          | 3.6 ± 1.8  | ...        | 0.10 ± 0.05     | 2.6 ± 1.1                  |

* Two Gaussian components were required to adequately fit the observed line profile.

### Note.
Spectra were Hanning smoothed to a resolution of 11.0 km s$^{-1}$. Uncertainties are the formal 1 $\sigma$ (68.3% confidence level) deviations of the data from the Gaussian fits.

The pressure-broadening width is proportional to $n_e^{7/4} T_e^{1/2} n_e$; thus, the pressure-broadened lines can be used to determine the true space electron density $n_e$ averaged over the nebula (Brocklehurst & Seaton 1972). Using $T_e$ of 7000 K, we find $n_e$ of $7 \times 10^6$, $9 \times 10^6$, and $3 \times 10^6$ cm$^{-3}$ based on the H53$\alpha$, H76$\alpha$, and H92$\alpha$ lines, respectively. The rms electron densities inferred from the 0.7, 2, and 3.6 cm continuum observations are $2 \times 10^5$ cm$^{-3}$, $9 \times 10^4$ cm$^{-3}$ (Sewilo et al. 2004, and in preparation), and $8 \times 10^4$ cm$^{-3}$ (Sewilo et al. 2004), respectively. The higher electron density from pressure broadening is expected, because it represents the actual space density of the gas that produces the broad lines, as opposed to the rms density derived from the radio continuum. The fact that the average density decreases with higher quantum transitions also suggests that each line in the range 0.7–3.6 cm samples different volumes of gas, as also suggested by the change in line velocity with transition.

The rms and true electron densities can be used to calculate the filling factor $f$ for the nebula. Equating the Strömgren relation for a uniform density region (in terms of $n_e$, rms) with that of a clumpy region (in terms of $n_e$, true) which is formed of $N$ smaller clumps, one obtains $N^3 f_{\text{clump}}^3 r_{\text{uniform}}^3 = n_e^3 \text{rms}/n_e^3 \text{true} = f$. This is the ratio of the volume occupied by the dense gas to the total volume of the H II region; thus $f$ is a measure of the degree of clumpiness of the nebula. Based on the 7 mm continuum and line data, we calculated the filling factor of $6 \times 10^{-4}$ for the highest density gas we sample in G28.20N.

### 5. SUMMARY

We have resolved the morphology and velocity structure of the HCHII region G28.20. The continuum emission has a shell-like structure, with an inner radius of 1100 AU, an outer radius of 2500 AU, and an rms density contrast of 2–3 between the central cavity and the torus.

Under the assumption that the H30$\alpha$ line is not significantly pressure broadened and that turbulence broadening is ~5 km s$^{-1}$,
we have resolved the contributions of thermal, turbulent, and pressure broadening from large-scale ordered motions. We suggest that the ordered motion has two components: a velocity gradient of $10^3 \, \text{km s}^{-1} \, \text{pc}^{-1}$ in the NE-SW direction along the minor axis, which may indicate rotation of a torus around a $28 \, M_\odot$ object; and line broadening (line splitting at some points) along the major axis, which may indicate lateral expansion of an outflow along the major axis of the nebula. In this scenario, the outflow axis would have to be in the plane of the sky, because line velocities along this axis are centered on the systemic velocity of the nebula. We suggest that the excess line broadening along the major axis is due to expansion of the outflow perpendicular to its axis.

The line width from large-scale motions averaged over the whole nebula is $\sim 10 \, \text{km s}^{-1}$. We find pressure broadening line widths for the H$53\alpha$, H$76\alpha$, and H$92\alpha$ lines of $\sim 28$, $\sim 50$, and $\sim 68 \, \text{km s}^{-1}$, respectively. These spatially unresolved, pressure-broadened lines were used to determine electron densities averaged over the nebula (not rms densities). The mean $n_e$ is $7 \times 10^6$, $9 \times 10^5$, and $3 \times 10^5 \, \text{cm}^{-3}$ based on the H$53\alpha$, H$76\alpha$, and H$92\alpha$ lines, respectively. These densities are 4–40 times higher than the rms densities derived from continuum data. The fact that the average electron densities decrease with higher quantum transitions is consistent with the change in opacity with frequency.

This study has for the first time resolved the contributions of thermal, turbulent, pressure, and ordered large-scale motions of BRRLs in a hypercompact H II region. The observations show that large-scale dynamics and high densities both contribute to BRRLs in G28.20N. This study was possible only because of the high angular resolution and sensitivity provided by the VLA.

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