1. INTRODUCTION

Compact H II regions are commonly observed in massive star-forming regions (Mezger, Schraml, & Terzian 1967; Garay & Lizano 1999). Reid & Ho (1985) first noted that a compact H II region in the G34.3+0.2 star-forming region had a cometary appearance, with a bright head and a diffuse tail. Rather than being a unique or even a rare source, G34.3+0.2 became the archetypal example of a class of sources now called cometary H II regions. The survey of Wood & Churchwell (1989) revealed that 20% or more of compact H II regions have cometary morphology.

Several models explaining the cometary appearance of compact H II regions have been proposed and actively debated. Reid & Ho (1985) first suggested that the cometary appearance of G34.3+0.2 could result from relative motion between an ionizing star and its surrounding molecular material, analogous to elongated structures predicted for such stars moving rapidly through the more diffuse interstellar medium (Weaver et al. 1977). This led to the “bow shock” model, which postulates supersonic motion of a star, with a strong stellar wind, through a molecular cloud (van Buren et al. 1990). An alternative model for the formation of cometary H II regions is the “champagne flow” model. This model assumes that the ionizing star is nearly stationary with respect to the molecular cloud but that the material surrounding the star has a steep density gradient (Israel 1978; Tenorio-Tagle 1979). Since the size and shape of an H II region are determined by the balance of ionization and recombination rates, an H II region will be “extended” in the direction of lowest density. In a uniform density gradient, this results in a parabolic shape for the ionized region, which can appear cometary. Other models for cometary H II regions are discussed by Gaume, Fey, & Claussen (1994), Raga (1986), and Gaume & Mutel (1987).

Harris (1973) published a high-resolution map at 5 GHz of the massive star-forming region DR 21. She noted two H II regions: a compact northern (D) and an extended southern source, with the southern source resolved into “three very compact condensations” (A, B, and C). Most discussion in the literature of these H II regions has followed the nomenclature of Harris, as well as her interpretation that the southern H II region’s condensations are independent compact sources excited by different stars. We recently mapped this region with higher angular resolution and sensitivity than Harris and discovered that both the northern and southern H II regions are cometary H II regions with nearly perpendicular symmetry axes projected on the sky. Figure 1 shows the 6 cm wavelength continuum emission from these sources, obtained from Very Large Array (VLA) B configuration data taken on 2001 April 23.

Finding twin cometary H II regions in one star-forming region provides a possibly unique opportunity to investigate the relative motion of cometary H II regions, as well as their internal velocity structures and overall motion with respect to nearby molecular material. Since the bow shock and champagne flow models predict different velocity structures, we undertook high angular resolution, spectral line observations to distinguish between these models. We used the VLA of the National Radio Astronomy Observatory (NRAO)1 to map two high-frequency radio recombination lines, to study motions in the plasma, and two ammonia (NH3) transitions, to study motions in the surrounding molecular material.

2. OBSERVATIONS AND DATA ANALYSIS

We observed DR 21 in two hydrogen recombination lines and two NH3 transitions using the VLA on 2001 December 23. The array was in the D configuration, with a minimum baseline of 0.033 km and a maximum baseline of 1.03 km. We obtained approximately 1 hr of on-source integration

1 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
time each for the H53α line (42951.97 MHz rest frequency) and the H66α line (22364.17 MHz rest frequency). The bandwidth for both recombination line observations was 12.5 MHz, which was divided into 32 channels of 390.625 kHz (or 2.73 and 5.25 km s\(^{-1}\) for H53α and H66α, respectively). The NH\(_3\) (1, 1) and (2, 2) transitions were observed in both right- and left-circular polarization with bandwidths of 3.125 MHz, divided into 64 channels of 48.828 kHz (or 0.62 km s\(^{-1}\)), and we obtained a total on-source integration time of ≈2 hr.

For both the recombination and NH\(_3\) line observations, the band center was set to an LSR velocity of −2.0 km s\(^{-1}\). The source 1331+305 was observed as a primary flux calibrator, 2015+371 as a secondary calibrator, and 2253+161 as a bandpass calibrator. We used the NRAO Astronomical Image Processing System (AIPS) to edit, calibrate, image, display the data, and make image cubes. For the hydrogen recombination line data, we made image cubes with tapered (6\(^\circ\) beam) and untapered (3\(^\circ\) beam) (\(u, v\))-data and used the tapered cubes to analyze the large southern H \(\pi\) region and the untapered cubes for the smaller northern H \(\pi\) region. Next, we generated spectra by summing the emission over “long slits,” approximately perpendicular to the major axes of the two cometary H \(\pi\) regions. We chose such long slits to increase signal-to-noise ratios and to facilitate comparison to models, which generally have axial symmetry about the cometary axis. The positions of these long slits are indicated on Figure 2, and the resulting spectra for the H66α transition are shown in Figure 3. To determine Doppler velocities, we fitted a Gaussian line profile to these spectra. The amplitude, central velocity, and FWHM of the Gaussian line profile were adjustable parameters, as well as two parameters

![Fig. 1.—Continuum emission from the dual cometary H \(\pi\) regions in DR 21 at 6 cm wavelength. Contour levels are 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, and 2 Jy beam\(^{-1}\). The ≈1.7 FWHM beam is indicated by the filled ellipse near the lower left corner. Ionized condensations labeled A, B, C, and D by Harris (1973) are indicated.](image)

![Fig. 2.—Continuum emission from the dual cometary H \(\pi\) regions in DR 21 at 1.3 cm wavelength. Contour levels are 0.02, 0.05, 0.1, 0.2, 0.5, 1, and 2 Jy. Dotted boxes indicate “long slit” areas over which spectra were summed for Gaussian fitting of the hydrogen recombination lines. Dashed boxes indicate the areas where NH\(_3\) emission spectra were generated; areas for NH\(_3\) absorption spectra cover most of the northern and southern H \(\pi\) regions and correspond approximately to regions N/1–N/3 and S/1–S/3, respectively. Labels near the boxes indicate position listed in Table 1. Line-center velocities from Gaussian fitting are given in kilometers per second with respect to the LSR in boldface in the center of the boxes. For the hydrogen recombination velocities, the average of H66α and H53α fits is indicated where both lines were detected.](image)
allowing for a linear spectral baseline. For both recombination lines, the spectral baselines typically sloped by about \( \pm 10\% \) of the peak amplitude of the line. Results of the Gaussian fits are given in Table 1 and Figure 3. While formal fitting errors usually were less than 0.3 km s\(^{-1}\), we estimate a more realistic error that allows for modeling uncertainty of \( \approx 1 \) km s\(^{-1}\).

We analyzed both \( \text{NH}_3 \) transitions and obtained nearly identical kinematic information from the two transitions, and for brevity we report here only the \( \text{NH}_3 \) (1, 1) transition results. The \( \text{NH}_3 \) (1, 1) transition main hyperfine component at a rest frequency of 23694.496 MHz was used to obtain Doppler velocities. Offset from the continuum sources, we detected the \( \text{NH}_3 \) in emission and produced spectra summed over long slits (see Fig. 2), as for the hydrogen recombination lines. Toward the cometary H\( \alpha \) regions, we detected \( \text{NH}_3 \) in absorption, and spectra were obtained by summing over regions that enclosed most of the continuum emission from each region. The spectra showed a small, but distinct, baseline curvature. Thus, we fitted a second-order baseline in addition to Gaussian lines to the spectra. The Gaussian fits to the main lines are given in Table 1. In Figure 3 we show the observed spectra and the best-fitting (three) Gaussians for the \( \text{NH}_3 \) main hyperfine

![Fig. 3.—\( \text{NH}_3 \) and H\( \alpha \) spectra toward the southern (left) and northern (right) cometary H\( \alpha \) regions in DR 21. Dotted vertical lines give the velocity for the molecular material as indicated by the \( \text{NH}_3 \) main hyperfine line absorption. Dashed sloping lines indicate the velocity of the ionized material, from the average of the H\( \alpha \) and H\( 3\alpha \) line fits, as one observes from head toward tail (top to bottom) along the cometary axes of the H\( \alpha \) regions.](image-url)
and inner satellite hyperfine components toward the H II regions and the H66α lines at positions along the cometary axes of the southern and northern H II regions.

3. DISCUSSION

The first explanation proposed for the cometary H II region morphology (Reid & Ho 1985) invoked relative motion between an ionizing star and its external molecular environment. For the archetypal cometary H II region, G34.3+0.2, Reid & Ho (1985) noted the presence of a supernova remnant to the west of the cometary region’s “head” and suggested that a stellar wind from the supernova’s precursor star might be responsible for the H II region’s cometary shape. The bow shock model, developed to explain cometary H II regions (van Buren et al. 1990; Mac Low et al. 1991; van Buren & Mac Low 1992), expanded upon this suggestion. It requires highly supersonic motion of a windblowing, ionizing star through dense surrounding material. On the other hand, a cometary appearance can also result from the ionization/recombination balance in a region with a strong density gradient, often called a champagne flow (Israel 1978; Tenorio-Tagle 1979). In addition, other forces may play a role in shaping cometary H II regions (Gaume et al. 1994).

In this section, we first address the possibility that in regions where ionized gas flows rapidly, hydrogen recombination line velocities may be difficult to interpret. Next, we briefly outline the dominant kinematic features of the bow shock and champagne flow models. Finally, we compare the observed velocities of the ionized and molecular material to these models and argue that they are mostly consistent with the predictions of the bow shock model.

3.1. Are Recombination Lines Reliable Velocity Indicators?

We observed two hydrogen recombination lines to assess whether the velocities measured by these lines differ significantly. Berulis & Ershov (1983) and Keto et al. (1995) discussed such an effect for W3OH, with line-center velocities shifting by ≈22 km s⁻¹ between the H110α and H35α lines. The shift in observed line-center velocity with transition is large for high principal quantum number (low-frequency) transitions and asymptotically approaches a constant at low principal quantum number (high-frequency) transitions. Keto et al. suggest that this transition-dependent velocity shift results from a combination of a large velocity gradient in the ionized material and a strong increase in line width for higher principal quantum number transitions, owing to collisional broadening. Since, for electron densities $\lesssim 10^7$ cm⁻³, collisional broadening is small for the H66α and lower principal quantum number transitions, we would expect that our recombination lines would not be sensitive to this complication.

For DR 21, we observe almost no shift in velocity between the H66α and H35α lines. The velocities of the H66α and H35α lines agree within 2 km s⁻¹ at all locations. For the northern H II region, the agreement is within the joint uncertainties (≈0.3 km s⁻¹). For the southern H II region, the H35α lines appear blueshifted by about 1.3 km s⁻¹ compared with the H66α lines at the same positions on the sky. The spectral baselines in the two transitions tended to slope in opposite directions, and small correlations between the spectral slopes and the center velocities might contribute to these small shifts.

Roelfsema, Goss, & Geballe (1989) mapped H76α recombination lines toward several positions over the DR 21 H II regions. The dual-cometary structure, clearly visible in our Figure 1 at 6 cm wavelength, is not as evident in their 14.7 GHz continuum image, and they did not use long slits to measure velocities along the symmetry axes of the cometary H II regions. Instead, they formed spectra at local peaks in the radio brightness, including one in the northern and five in the southern H II region. Toward the northern H II region (their position D) the H76α line peaked at 4.6 km s⁻¹, in good agreement with the average of our regions N/1–N/3, which span velocities of 4.1–5.9 km s⁻¹. Toward the head of the southern H II region, Roelfsema et al. (1989) measured a velocity (at their position A) of –4.1 km s⁻¹, which compares well with our measurement of –3.3 km s⁻¹ for region S/1. In addition, their H76α measurements at positions B and C yielded velocities of –1.2 and –3.2 km s⁻¹; these positions if combined correspond to summing our regions S/2 and S/3 for which we measure velocities of –1.6 and –3.0 km s⁻¹. Again this indicates good agreement between the H76α measurements of Roelfsema et al. (1989) and ours at H66α and H35α.

In conclusion, since (1) on average the H76α, H66α, and H35α lines are in agreement to within $\lesssim 1$ km s⁻¹, (2) the widths of these lines are nearly identical, and (3) exceptionally high densities would be required to yield any substantial velocity shift between H66α and H35α lines, we conclude that the velocities measured by these high-frequency
recombination lines are not significantly affected by strong velocity gradients coupled with collisional broadening. Thus, the lines should indicate the line-of-sight velocity of the ionized material in the dense HII regions to within about 1 km s\(^{-1}\).

3.2. The Bow Shock Model

The bow shock model, as formulated by van Buren et al. (1990), postulates a balance between the stellar wind pressure and the ram pressure of dense molecular material caused by the motion of the star through a dense molecular cloud. This gives rise to an HII region in the form of a thin, paraboloidal shell. The volume between the thin ionized shell and the star is mostly evacuated by the stellar wind, and this model predicts limb brightening in the tail, which is characteristic of cometary HII regions (see Fig. 1).

The bow shock model predicts that the ionized material near the cometary head should be moving, on average, with the velocity of the star (and hence the ionized gas should be moving rapidly with respect to the molecular gas of the surrounding cloud). Farther down the cometary tail the velocity of the ionized gas should approach that of the molecular cloud (see Fig. 4).

3.3. The Champagne Flow Model

The champagne flow model evolved from “blister” models for compact HII regions (Israel 1978) and also can yield cometary morphology (Tenorio-Tagle 1979; Yorke, Tenorio-Tagle, & Bodenheimer 1983). The champagne flow model postulates that cometary HII regions form when ionized gas expands asymmetrically out of a dense clump within a molecular cloud into a lower density region. In this model, the velocity of ionized gas near the cometary head should be close to the velocity of the densest molecular gas, whereas down the cometary tail, the ionized gas should attain high velocities of \(\approx 30\) km \(s^{-1}\) as the ionized material is accelerated by a strong pressure gradient through the “nozzle” (Bodenheimer, Tenorio-Tagle, & Yorke 1979; Yorke et al. 1983). Thus, the predictions of the champagne flow model, shown schematically in Figure 4, are nearly opposite those of the bow shock model with respect to the velocity field.

3.4. The DR 21 Cometary HII Regions

The Doppler velocities of the NH3 lines seen in absorption toward the cometary HII regions are \(\approx -1.5\) km \(s^{-1}\), and the emission lines north and south of these HII regions differ by \(\leq 1\) km \(s^{-1}\) from this value. Thus, the molecular material, presumably in close proximity to the ionized material, shows little velocity structure. On the other hand, the ionized material, as indicated by hydrogen recombination lines, is clearly kinematically different from the molecular material. The northern HII region has a velocity, at the brightest emission near the cometary head, which is redshifted by 7 km \(s^{-1}\) with respect to the molecular gas, whereas the southern HII region appears blueshifted by 2 km \(s^{-1}\). Assuming random orientations for the velocity vector of these HII regions (with an average inclination to the line of sight of \(60^\circ\)), this suggests space velocities (three-dimensional speeds) of about 15 and 4 km \(s^{-1}\) relative to the molecular material. This supports a bow shock model and opposes a champagne flow model.

Since the cometary appearance of an HII region becomes more pronounced as the structure is viewed from the side (i.e., the closer the cometary axis is to being in the plane of the sky), the space velocities are likely to be greater than those estimated for random orientations. Indeed, the long cometary “tail” of the southern HII region, compared with the short “tail” of the northern HII region, suggests that the southern HII region may have its cometary structure nearly in the plane of the sky. If this is true, then most of its space velocity may be in the plane of the sky, and only a small component of the space velocity would be indicated by its Doppler velocity. Thus, it would not be surprising if the space velocity of the southern HII region is \(\approx 5–10\) km \(s^{-1}\) with respect to the ambient molecular material, as for the northern HII region.

For both HII regions, the measured velocities change with position along the cometary axis. Starting at the head and moving down the tail of the cometary HII regions, the velocities approach that of the ambient molecular material. This is in keeping with the bow shock model. For the southern HII region, there is an indication, at position S/4, that the velocity of the ionized material “drifts past” that of the ambient molecular material, as indicated by the NH3 velocities. Roelfsema et al. (1989) report H76\(\alpha\) lines from two positions farther down the tail than our S/4 position with velocities of 12.6 and 4.2 km \(s^{-1}\). This could indicate the beginning of a pressure-driven outflow down the tail of the cometary HII region, as suggested by champagne flow models. Indeed, there is no reason that a bow shock and champagne flow could not operate in the same cometary HII region (e.g., as in the hybrid model in Fig. 4). However, more sensitive hydrogen recombination line observations than we have achieved will be needed to measure velocities of the ionized material farther down the cometary tails.

4. COMPLICATIONS AND FUTURE WORK

In this paper, we have analyzed the velocity of the ionized material only along the cometary axes of the HII regions in DR 21. For the northern cometary HII region, there is no evidence for velocity structure perpendicular to the
cometary axis. However, for the southern cometary H II region, there are indications of velocity structure perpendicular to the cometary axis. In this source, deviations from axial symmetry seem to grow in the weak, diffuse tail. Given our current sensitivity, we cannot properly characterize the kinematic asymmetry of the ionized gas in the cometary tails.

Deviations from axial symmetry are also seen in the archetypal cometary H II region G34.2+0.2 (Garay, Rodriguez, & van Gorkom 1986). Neither the bow shock nor the champagne flow model, at its simplest form, predicts such structure. However, one might expect complex kinematics for the ionized material in cometary H II regions, owing to possible anisotropic stellar winds, the effects of magnetic fields, and/or misoriented stellar motions and molecular cloud density gradients. Perhaps future observations with the VLA, which can yield a factor of \( \gtrsim 3 \) increase in sensitivity over our current data, will better characterize these effects and lead to a more complete understanding of cometary H II regions.

The widths of hydrogen recombination lines may provide information that can help discriminate among various models. Thermal line widths for an 8000 K hydrogen plasma are expected to be \( \approx 20 \) km s\(^{-1}\). We observed broader line widths of \( \approx 30 \) km s\(^{-1}\) for both cometary H II regions, indicating nonthermal components of \( \approx 20 \) km s\(^{-1}\). This could be caused by the effects of flows within the H II regions, driven by strong stellar winds. Note that the measured line widths are relatively constant over the regions measured. The bow shock model, in its simplest form, predicts line widths greatest at the head and decreasing toward the tail of a cometary H II region. Alternatively, the champagne flow model predicts line widths greatest down the tail as material is strongly accelerated. Thus, the line width data do not strongly support either model. However, as discussed above, plasma flows within the cometary H II regions may be quite complex and will complicate interpretation of line widths.

Finally, on angular scales \( \approx 10 \) times larger than considered in this paper, the DR 21 star-forming region displays rich and complex structure. In a series of papers, Garden and collaborators (Garden et al. 1986, 1991a, 1991b; Garden & Carlstrom 1992) discovered that the DR 21 H II regions are seen projected toward the center of a structure about 6' long oriented approximately in the northeast-southwest direction. This structure was detected in vibrational H\(_2\) as well as rotational CO and HCO\(^+\) line emission. They argue that this structure is an extremely luminous bipolar outflow associated with the southern H II region discussed in this paper. Given the location of the southern H II region and the close alignment of its cometary axis with that of the axis of elongated structure, it is reasonable to consider the star (or stars) powering the H II region as responsible for a bipolar outflow that excites the vibrational H\(_2\) emission. However, in this case it is difficult to reconcile the sharp western edge of the southern cometary H II region with the implied bipolar outflow. Unless the western outflow was formed prior to the H II region, the outflow would need to pierce the edge of the H II region without disrupting it or producing an observable effect. This seems unlikely but needs further analysis.

Garden et al. (1991a) point out that the vibrational H\(_2\) emissions of DR 21 and Orion are similar. For the case of Orion, even though the source is much closer than DR 21, the origin of the high-velocity flow seen in both H\(_2\)O masers and vibrational H\(_2\) emission is unclear (Genzel et al. 1981; Nadeau, Neugebauer, & Geballe 1982). Moved to the distance of DR 21, some of the candidate sources for the outflows in Orion, such as source I and source N (Menten & Reid 1995), would be separated by less than \( \approx 1'' \). Neither of these sources excites a strong H II region. Were a different source to excite a strong H II region in Orion, similar to the southern cometary H II region in DR 21, the candidate sources would be difficult to distinguish, let alone identify. Thus, one possible explanation for the approximate coincidence of the southern H II region with the center of the elongated bipolar-like structure in DR 21 is that they are excited by different sources at different depths in the same massive star-forming region and are otherwise unrelated.

REFERENCES
Berulis, I. I., & Ershov, A. A. 1983, Soviet Astron. Lett., 9, 341
Bodenheimer, P., Tenorio-Tagle, G., & Yorke, H. W. 1979, ApJ, 233, 85
Garay, G., & Lizano, S. 1999, PASP, 111, 1049
Garay, G., Rodriguez, L. F., & van Gorkom, J. H. 1986, ApJ, 309, 553
Garden, R., Geballe, T. R., Gatley, I., & Nadeau, D. 1986, MNRAS, 220, 203
———. 1991a, ApJ, 366, 474
Garden, R. P., & Carlstrom, J. E. 1992, ApJ, 392, 602
Garden, R. P., Hayashi, M., Hasegawa, T., Gatley, I., & Kaifu, N. 1991b, ApJ, 374, 540
Gausse, R. A., Fey, A. L., & Claussen, J. M. 1994, ApJ, 432, 648
Gaume, R. A., & Mutel, R. L. 1987, ApJS, 65, 193
Genzel, R., Reid, M. J., Moran, J. M., & Downes, D. 1981, ApJ, 244, 884
Harris, S. 1973, MNRAS, 162, 5P
Israel, F. P. 1978, A&A, 70, 769
Keto, E. R., Welch, W. J., Reid, M. J., & Ho, P. T. P. 1995, ApJ, 444, 765
Mac Low, M., van Buren, D., Wood, D. O. S., & Churchwell, E. 1991, ApJ, 369, 395
Menten, K. M., & Reid, M. J. 1995, ApJ, 445, L157
Mezger, P. G., Schraml, J., & Terzian, Y. 1967, ApJ, 150, 807
Nadeau, D., Neugebauer, G., & Geballe, T. R. 1982, ApJ, 253, 154
Raga, A. C. 1986, ApJ, 300, 745
Reid, M. J., & Ho, P. T. P. 1985, ApJ, 288, L17
Roelfsema, P. R., Goss, W. M., & Geballe, T. R. 1989, A&A, 222, 247
Tenorio-Tagle, G. 1979, A&A, 71, 59
van Buren, D., & Mac Low, M. 1992, ApJ, 394, 534
van Buren, D., Mac Low, M., Wood, D. O. S., & Churchwell, E. 1990, ApJ, 353, 570
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377
Wood, D. O. S., & Churchwell, E. 1989, ApJS, 69, 831
Yorke, H. W., Tenorio-Tagle, G., & Bodenheimer, P. 1983, A&A, 127, 313