

H I “TAILS” FROM COMETARY GLOBULES IN IC 1396

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ABSTRACT

IC 1396 is a relatively nearby (750 pc), large ($>2^\circ$), H II region ionized by a single O6.5 V star and containing bright-rimmed cometary globules. We have made the first arcminute resolution images of atomic hydrogen toward IC 1396, and have found remarkable “tail”-like structures associated with some of the globules and extending up to 6.5 pc radially away from the central ionizing star. These H I “tails” may be material which has been ablated from the globule through ionization and/or photodissociation and then accelerated away from the globule by the stellar wind, but which has since drifted into the “shadow” of the globules. This report presents the first results of the Galactic Plane Survey Project recently begun by the Dominion Radio Astrophysical Observatory.

Subject headings: H II Regions — ISM: globules — ISM: individual (IC 1396)

1. INTRODUCTION

IC 1396 (S131; Sharpless 1959) is a nearby (750 pc; Garrison & Kormendy 1976), large (greater than 2°), evolved H II region ionized by a single O6.5 V star HD 206267 located near its center. Within the H II region are many dark globules, some with bright rims facing toward the central ionizing star (Pottasch 1956, 1958a, b; Osterbrock 1957). Since the pioneering work of Pottasch and Osterbrock, these globules have been studied in radio continuum, molecular emission, and optically (for a summary of these studies see Patel et al. 1995). For example, Patel et al. (1995) have mapped the CO emission within the H II region, and have found that the bright-rimmed globules appear to trace a ring approximately 12.5 pc in radius which is expanding radially outward from the central star. The expansion is apparently caused, not by the stellar wind or radiation pressure, but by a “rocket effect” (Harwit & Schmid-Burgk 1983) induced by the ionization of the inner-facing surface of the globules (the “bright rims”). Weikard et al. (1995) have also mapped the H II region in several transitions and isotopomers of CO and in H I, but at moderate resolution (several arcminutes).

In this Letter we present the first high-resolution ($\sim 1'$) images of atomic hydrogen toward IC 1396, showing remarkable “tails” of H I associated with some of the globules. (A more detailed analysis, presenting all of the data, awaits a later paper.) These are the first results of the Galactic Plane Survey (GPS) recently begun by the Dominion Radio Astrophysical Observatory (DRAO).¹ The GPS is being carried out by a consortium of Canadian and international astronomers, and will provide an image of the Galactic plane in the longitude interval 75° – 145° and latitude range -3° to $+5^\circ$, yielding an atomic hydrogen (H I) spectral line data cube with 256 velocity

channels and angular resolution of $1' \times 1' \text{ csc } \delta$. At the same time, continuum images at 1420 MHz and 408 MHz are obtained, with full polarization data at 1420 MHz. Observations began in 1995 March and will continue for approximately 4 yr.

2. OBSERVATIONS

The observations presented in this work were obtained using the Synthesis Telescope (ST) of the Dominion Radio Astrophysical Observatory (DRAO), in 1995 March and April. The array consisted of seven 9 m antennas in an east-west configuration, observing simultaneously $\lambda 21$ cm and $\lambda 74$ cm continuum and the H I emission line at 1420.406 MHz. (The $\lambda 74$ cm observations, though available, were not used in this study.) The total bandwidth of the $\lambda 21$ cm maps is 30 MHz. The H I data were acquired with a new 256 channel spectrometer using a bandwidth of 1 MHz. This corresponds to a channel spacing of 0.824 km s^{-1} with resolution 1.32 km s^{-1} . By tracking a field center for 12 hr and moving the three mobile antennas between trackings, a complete u - v coverage is obtained with baselines from 12 m to 600 m at 4.3 m intervals.

Maps were made by Fourier transforming the edited, calibrated, and gridded visibilities. The $\lambda 21$ cm maps were then cleaned and self-calibrated. The H I data were not cleaned because of the nearly complete u - v coverage and low sidelobe levels (less than 4%), and because the dynamic range within each map (≈ 60) was generally insufficient to warrant cleaning. Continuum emission was subtracted from the H I maps, using an uncleaned continuum map.

Extended structure, corresponding to interferometer spacings less than 12 m, was extracted from single-dish maps. At $\lambda 21$ cm, these were obtained from surveys published by Reich (1982) and Reich & Reich (1986, 1988). Single-dish H I data were obtained using the DRAO 26 m telescope in 1995 July, and were calibrated by observations of the standard region S7

¹ The Dominion Radio Astrophysical Observatory is operated as a national facility by the Herzberg Institute for Astrophysics of the National Research Council of Canada.

(Williams 1973). The ST and single-dish maps were Fourier transformed, filtered and tapered in a complementary manner, then retransformed. The ST maps were then corrected for the 9 m polar diagram, and added to the filtered single-dish maps. In this way we obtain maps containing full coverage of all structure down to the resolution of the synthesized maps, which is $\sim 67'' \times 59''$ with major axis oriented at position angle 4° east of north. The rms noise in the H I maps at the field center is ~ 2.9 K (T_B) per channel. Three fields, with field centers separated equally by $\sim 95'$, were conjoined in a mosaic so that the noise is relatively constant over much of the image. The full images will be presented in a later paper.

3. THE DATA

While searching for H I associated with the bright rims, we discovered remarkable H I features associated with bright rims A and B (located $17'$ and $37'$ almost due west of the illuminating star), and with rim F (located $\sim 1'$ north-east of the illuminating star). (Nomenclature is from Pottasch 1956.) In Figure 1 (*top*; Plate L10) we show the A/B complex of rims/globules from the classic red/H α image made by Osterbrock (1957). Figure 1 (*above center*) is a gray-scale map of $^{12}\text{CO } J = 1-0$ emission from Patel et al. (1995), labeled with the rim/globule nomenclature of Pottasch (1956) and Patel et al. (1995). Figure 1 (*below center, bottom*; Plate L10) shows the 21 cm continuum and H I emission respectively from this region. The H I emission was integrated over the velocity interval -6 to -14 km s $^{-1}$, and “background” emission was removed by subtracting a twisted plane fitted to a box defined by the edges of the image. (The “background” emission was subtracted in order to isolate the H I in the vicinity of the globules.) Figure 2 (Plate L11) shows a similar quartet of images of globule F, including H I integrated over the velocity interval -2 to $+5$ km s $^{-1}$. Despite a careful search, no such features were seen toward any of the other globules.

The H I morphology is clearly related to the globules and is quite remarkable. In the immediate vicinity of globule A (designated globule 18 by Patel et al. 1995) the H I forms a distinct “ring,” with a “tail” extending $\sim 10'$ behind the ring opposite the direction of the O6.5 star. H I also seems to trail behind the ridge of CO extending south-west of A (i.e., globule 14 from Patel et al. 1995), and perhaps from the small CO cloud (globule 15) to the south. The H I tail from globule 14 extends west until a bright knot of H I south and west of (i.e., behind) B (globule 13). The other CO globules in this group (globules 12 and 10) also appear to have H I associated with them immediately adjacent to the south and west. Behind the B complex, another tail of H I extends $\sim 30'$ due west and ends beyond the edge of the H II region. At the distance of IC 1396 (750 pc), this implies a projected length of ~ 6.5 pc.

The $\lambda 21$ cm continuum image (Fig. 1 [*below center*; Pl. L10]) shows bow-shaped ionization fronts associated with many, but not all, of the globules, and which closely trace the bright rims. Also visible is a “shadow” west of globule 12 extending to the edge of the H II region. Our image is very similar to the 21 cm continuum map of the A and B bright rims made by Matthews (1979).

The $\lambda 21$ cm image of globule F (Fig. 2 [*bottom left*; Pl. L11]) clearly shows a bow-shaped ionization front on the leading edge of the globule (designated 31 in Patel et al. 1995), as well as a weaker, more diffuse ridge along the front edge of globule 32. (The illuminating star HD 206267 is located $\sim 1^\circ$ approx-

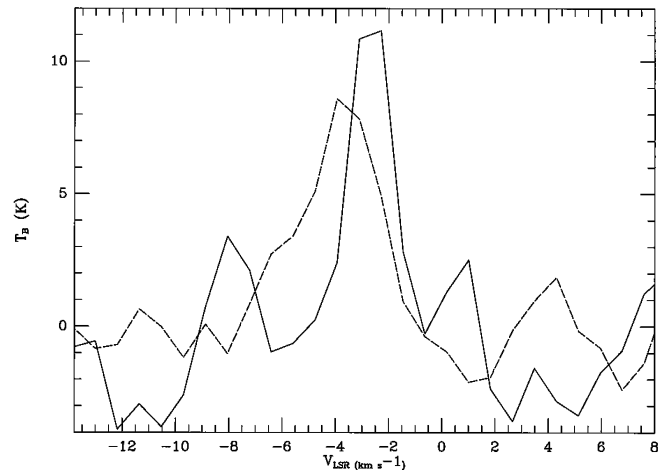


FIG. 5.—Background-subtracted H I spectra in the vicinity of globule F were averaged over the H I “head” (solid line) and “tail” (dashed line), and are shown here.

imately south-west of F.) The H I (Fig. 2 [*bottom right*; Pl. L11]) is weaker and less clearly defined than that associated with A and B, but its fan-shaped tail is clearly associated with the CO (Fig. 2b [Pl. L00]).

Channel maps at a few velocities of the H I associated with globules A and B are shown in Figure 3 (Plate L12). Over the four channels shown here, which represent most of the velocity range of this feature, the “head” (i.e., H I ring in globule A) and “tail” (i.e., the rest) show very little relative change. (From -6 to -8 km s $^{-1}$ there is significant emission north-west of globule A, but it is unclear if or how this relates to the rest of the H I.) In Figure 4 (Pl. L13) we show a spatial-velocity plot, made by averaging a 10 pixel wide ($\sim 6'$) row in R.A. centered at declination $57^\circ 30' 58''$. The center velocity of the H I is constant through the whole length of the H I feature. The centroid velocity of the H I associated with globule A is -9.3 km s $^{-1}$ and with B is -9.8 km s $^{-1}$. (Emission at velocities $\lesssim -15$ km s $^{-1}$ and $\gtrsim -2$ km s $^{-1}$ is not related.) There does not appear to be any velocity gradient within the H I, although the gas associated with each globule may be at slightly different velocities.

In Figure 5 we display “background-subtracted” H I spectra, found by averaging H I emission in the immediate vicinity of globule F (31), shown as a solid line, and toward the H I “tail” of F, shown as a dashed line. The H I line from the “tail” (dashed line) is significantly broader (FWHM ~ 3.5 km s $^{-1}$) and blueshifted ($V_{\text{cen}} \sim -4.0$ km s $^{-1}$) compared to the “head” (solid line, FWHM ~ 2 km s $^{-1}$, and $V_{\text{cen}} \sim -2.7$ km s $^{-1}$).

4. DISCUSSION

The morphology of the H I associated with these globules is remarkable and is reminiscent of comets in the solar system. One possibility for the origin of the H I “tails” is that, like solar system comets, they represent material which has been ablated from the globule through ionization and/or dissociation and then accelerated away from the globule by stellar wind from the central O star. In this scenario, the H I should be moving outward from the globules radially away from the central star, at velocities greater than that of the globules. Patel et al. (1995) found the velocity of the CO emission from A (and associated globule 14) to range from -7.9 to -8.2 km s $^{-1}$, while the globules in the vicinity of B (including 10, 12 and 13)

PLATE L10

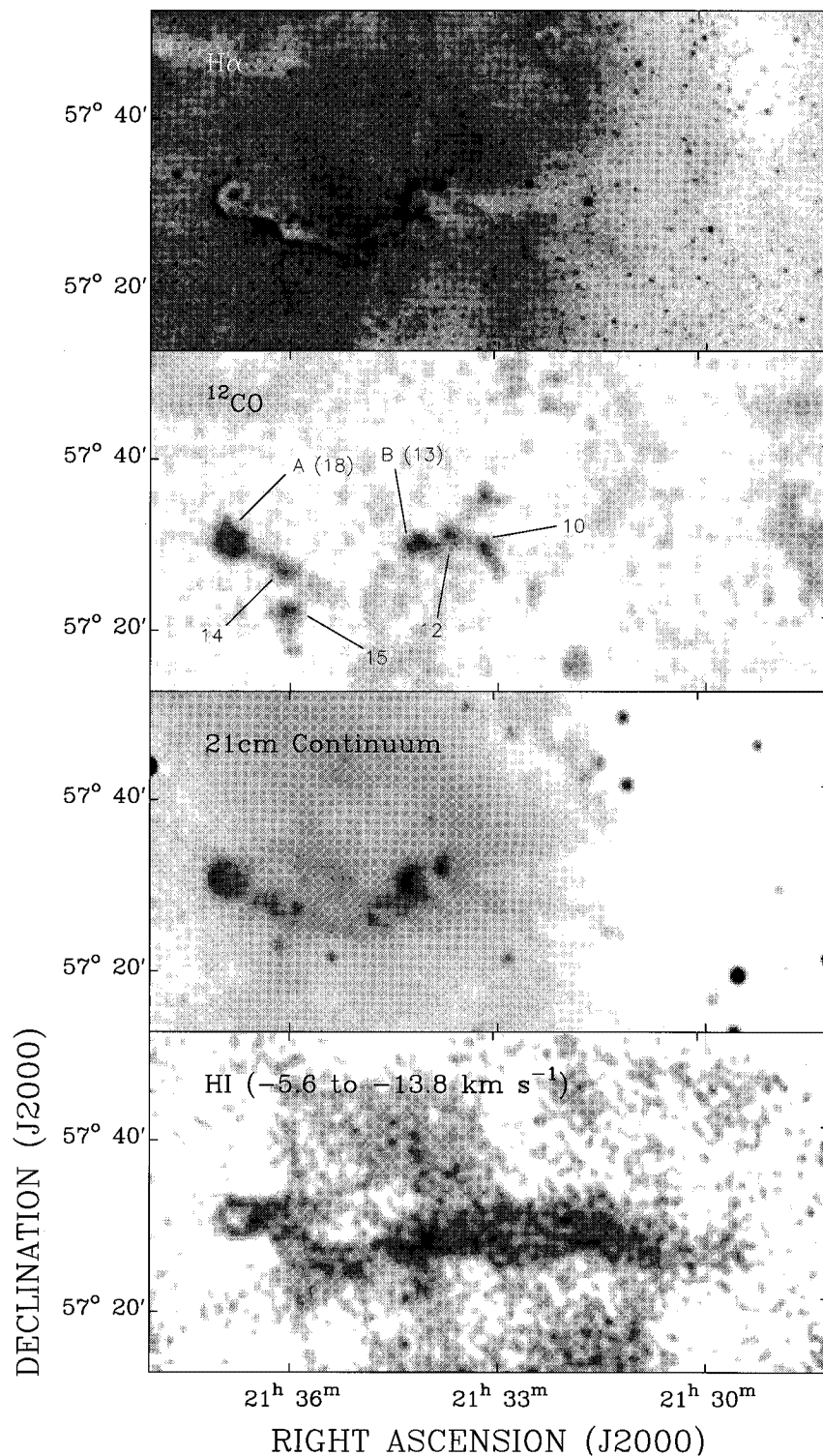


FIG. 1.—Panels, from top to bottom, are Red/H α print from Osterbrock (1957) showing the bright rims and dark globules in the vicinity of globules A and B. Gray scale in this and in figures below is linear; map of $^{12}\text{CO } J=1-0$ peak intensity from Patel et al. (1995), where labels refer to rim/globule nomenclature of Pottasch (1956) and Patel et al. (1995); gray scale of 21 cm continuum emission; atomic hydrogen emission integrated over velocity interval -5.6 to -13.8 km s $^{-1}$. Background emission has been subtracted by removing a twisted plane fitted to the edges of the displayed box.

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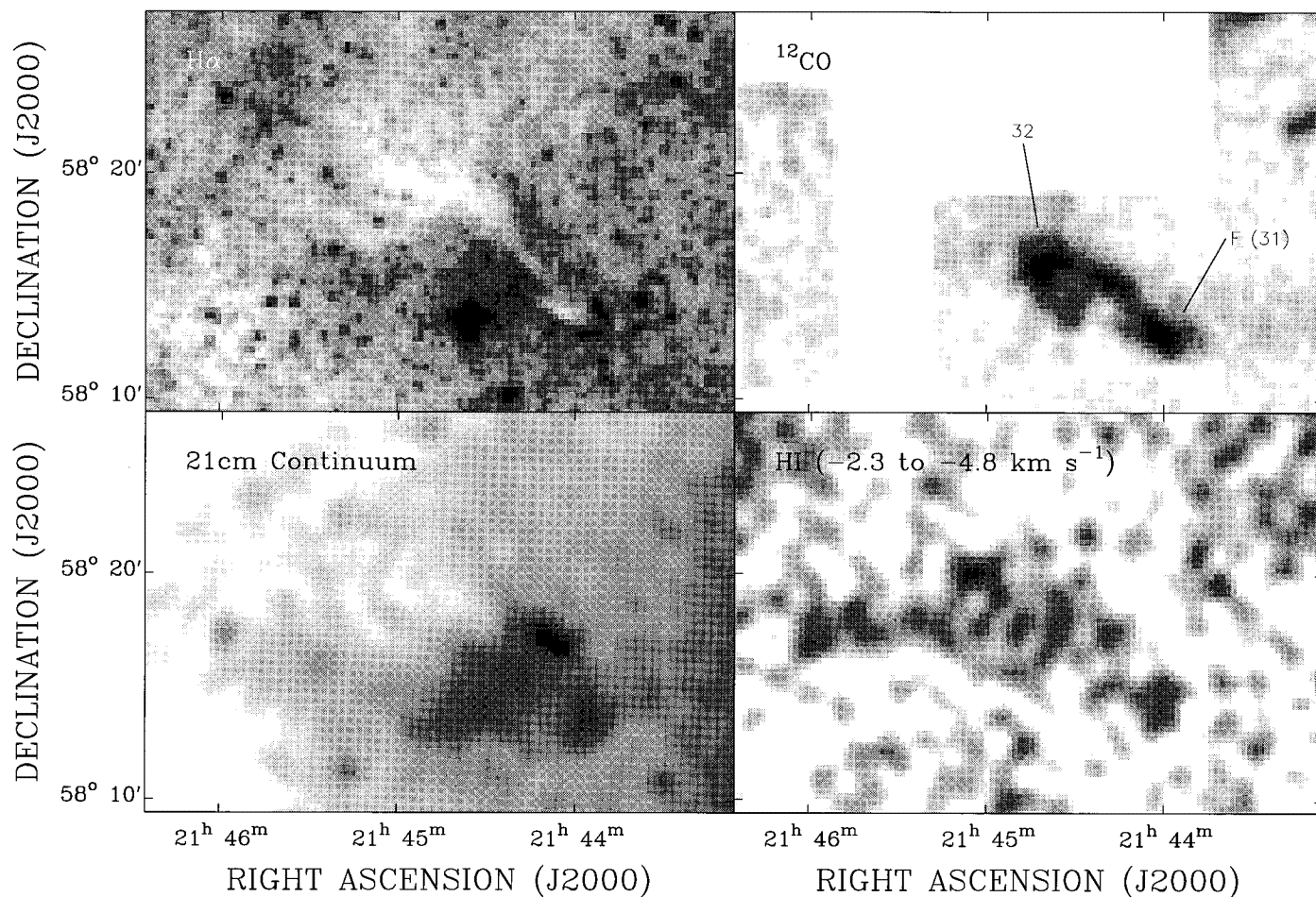


FIG. 2.—*Top left panel:* red print from Osterbrock (1957) showing the bright rims and dark globules in the vicinity of globule F. *Top right panel:* Nyquist-sampled map of $^{12}\text{CO } J = 1-0$ peak intensity from Patel et al. (1995). Labels refer to rim/globule nomenclature of Pottasch (1956) and Patel et al. (1995). *Bottom left panel:* $\lambda 21$ cm continuum emission. The 3 K contour of ^{12}CO is also shown. *Bottom right panel:* atomic hydrogen emission integrated over velocity interval -2.3 – 4.8 km s^{-1} . Background emission has been subtracted by removing a twisted plane fitted to the edges of the displayed box. The 3 K contour of ^{12}CO has been overlaid.

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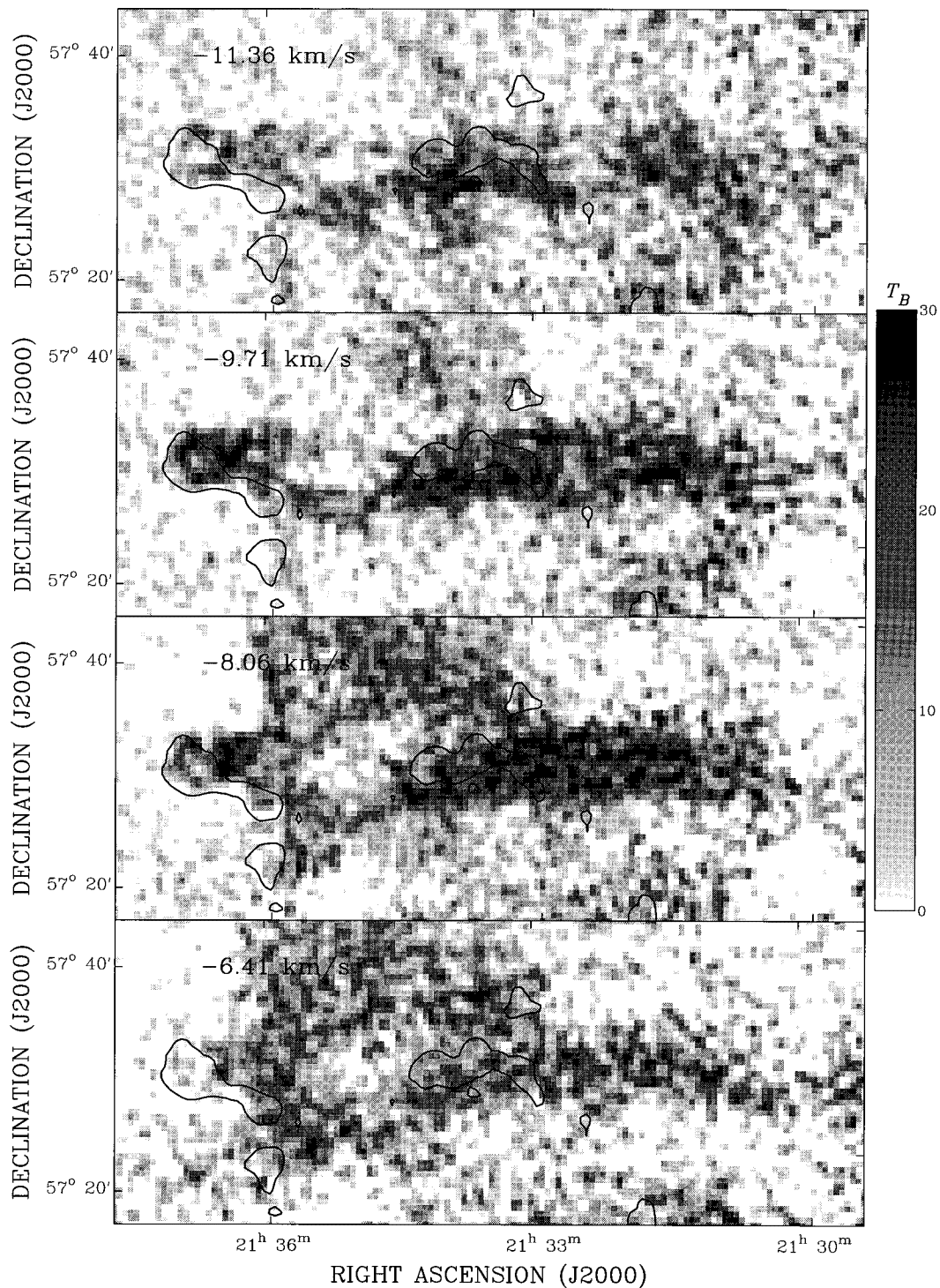


FIG. 3.—Maps of selected channels of H I emission in the vicinity of globules A and B. Background emission has been subtracted by removing a twisted plane fitted to the edges of the box displayed in Figure 1. The 4 K contour of ¹²CO has been overlaid on each image. Gray scale intensities are shown by the “wedge” at right.

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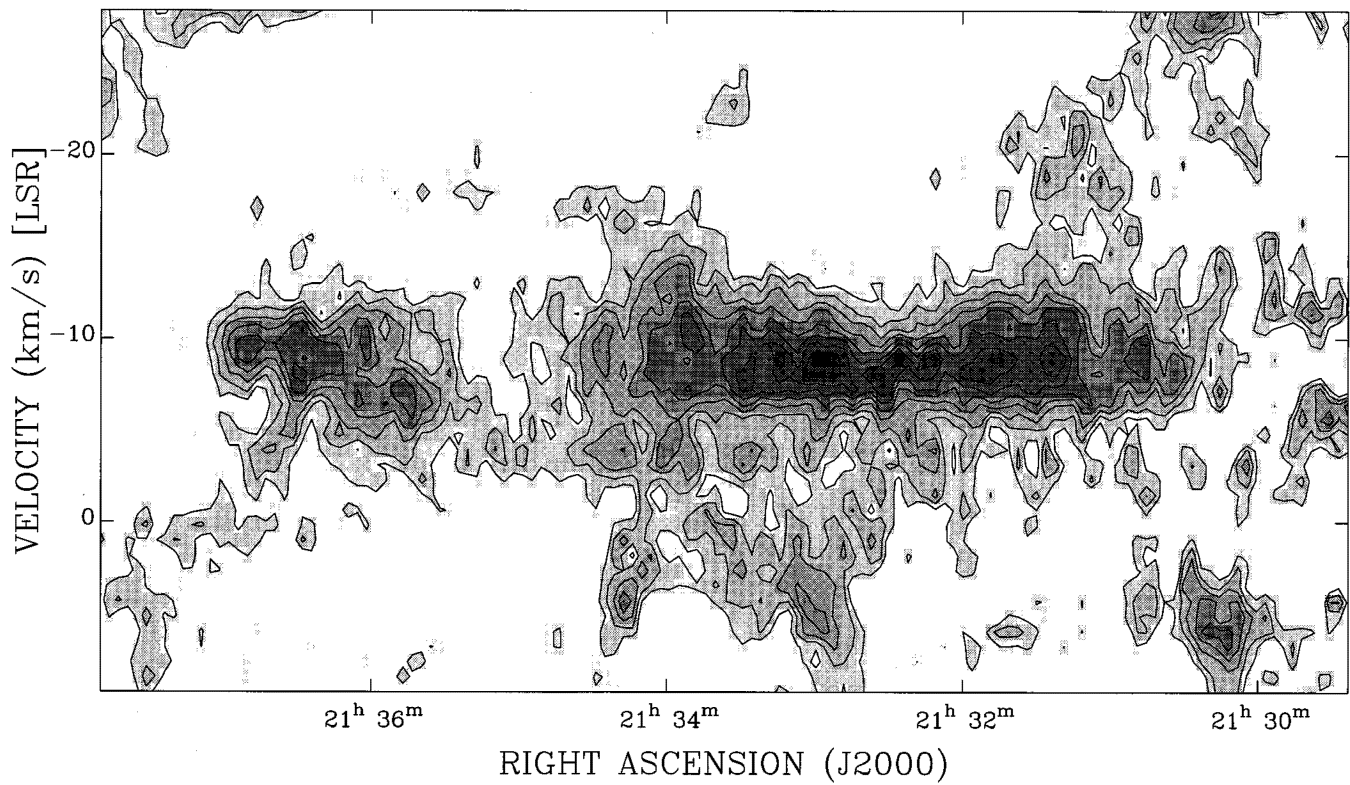


FIG. 4.—Spatial-velocity diagram of (background-subtracted) H I along a cut through globules A and B, averaging 10 pixels in the declination direction. Contours are every 3 K (brightness temperature T_B).

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range from -4.8 to -5.6 km s $^{-1}$. The H I associated with A is thus blueshifted by more than 1 km s $^{-1}$, and that associated with B by more than 4 km s $^{-1}$. The CO velocity of globule F is -3.2 km s $^{-1}$. In this case, the H I in the “head” is slightly redshifted compared to the CO (by ~ 0.5 km s $^{-1}$), while the “tail” is blueshifted (by ~ 0.8 km s $^{-1}$). Patel et al. (1995) found that the CO globules appear to trace an expanding ellipse. The radial components of the expansion velocities for globules A, B, and F are toward the line of sight, so that if the H I is being blown away from the globules by the stellar wind, the velocity of the H I should be blueshifted with respect to that of the CO as we observe (except for the “head” of F). However, in this scenario we might also expect to see an increase in the velocity of H I with increasing distance from the central star if the stellar wind were to continue accelerating the gas, as we clearly do not see for the “tails” of A and B, and in addition one might expect the gas in the accelerated tails to be ionized.

A second possibility is that the H I “comets” are ambient material, perhaps predating the H II region, which lies within the “shadow” of the globules protecting it from ionization or acceleration. In this case, since the globules have been accelerated by the “rocket effect” (Harwit & Schmid-Burgk 1983) while the H I should have been relatively undisturbed, the H I should be redshifted with respect to the CO. Except for the “head” of F, this is not the case.

A third scenario is that the H I is material which, as in the first possibility above, has been ablated and accelerated from the globules, but the material has drifted into the shadow of the globules where it is sheltered from further ionization or acceleration. Qualitatively, this scenario seems the most attractive of the three, since it can account for the blueshifted H I relative to the CO and the lack of acceleration. We can calculate the mass of atomic hydrogen in these H I “comet tails” by assuming that the optical depth is small. Then $N_{\text{HI}} = 1.823 \times 10^{18} \int T_b dv \text{ cm}^{-2}$ (Kraus 1982). The mass of H I associated with globules A and B is then $22 M_{\odot}$ ($\sim 4 M_{\odot}$ associated with A, $\sim 18 M_{\odot}$ with B), which is $\approx 5\%$ of the total mass of molecular gas within these globules (Patel et al. 1995). The mass associated with F is $1.5 M_{\odot}$ ($\sim 0.25 M_{\odot}$ in the “head”, $\sim 1.25 M_{\odot}$ in the “tail”), which is less than 2% of the molecular mass.

Is there, however, sufficient momentum flux in the stellar wind to have accelerated this material by several km s $^{-1}$? Chlebowski & Garmany (1991) have determined the mass-loss rate and wind terminal velocity of HD 206267 to be $\dot{M} = 7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ and $V_{\infty} = 3.1 \times 10^3$ km s $^{-1}$. Thus the momentum flux over 4π sr is $\approx 2.1 \times 10^{-3} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$. If we assume a 1 pc diameter globule, roughly 12.5 pc from the central star (the approximate current radius of the expanding ring; Patel et al. 1995), then $\Omega/4\pi \approx 0.04$ and the momentum flux on the globule is $\approx 8.4 \times 10^{-5} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$. The dynamical ages of these tails, neglecting the inclination of the velocity vector to the line of sight, are 1.6–2.5 Myr, which is roughly the age of the H II region. The material could have been accelerated for only a short fraction of that time, say $\approx 5\%$ or $\sim 10^5$ yr. In the immediate vicinity of globule A is $\sim 1 M_{\odot}$ of atomic gas. Over $\sim 10^5$ yr, $1 M_{\odot}$ of material would be accelerated to ~ 8 km s $^{-1}$.

It is thus plausible that the tails are material which was initially ablated and accelerated from the globules, but is now in the shadow of the dense globules. There remains the “head” of the H I comet associated with F, which is redshifted rather than the expected blueshifted. According to the “rocket

effect” model of Harwit & Schmid-Burgk (1983), it is the action of material being ionized/dissociated on the front surfaces of the globules which accelerates it away from the star. The H I “head” of F might be the initially redshifted “rocket-exhaust” before being accelerated itself by the stellar wind. However, we see no such red-shifted emission on the front surface of globule A (Fig. 4).

Finally, the ringlike H I structure surrounding globule 18 (rim A) is intriguing. No other globule seems to possess a similar structure. The globule itself is unusual, with a central cavity or hole which can be seen both optically (Fig. 1 [Pl. L10]) and in molecular emission (Wooten et al. 1983; Nakano et al. 1989; Patel et al. 1995). Inside the cavity are two stars, LkH α 349 and LkH α 349/c, which are young stellar objects, the former of which may be on its way to becoming a Herbig Be star (Hessman et al. 1995). These stars are unlikely to have ionized or dissociated the gas in the cavity. Instead, the cavity was likely evacuated during an earlier outflow stage of one or both of these stars (Nakano et al. 1989).

Near the outside edge of the “backside” of the globule, $\sim 100''$ south-west of LkH α 349, is a B3V star VDB 142 (HD 239710, AG+57 1457). Optical images of the region (Osterbrock 1957; P. Boltwood 1996 private communication) show that this star is surrounded by diffuse nebulosity, suggesting that this star is physically associated with the globule. A B3V star can create a small H II region and a larger H I photodissociation region (Roger & Dewdney 1992). There is some indication of an enhancement of H I intensity toward this star. Thus the ring morphology of this globule may be the result of ionization and photodissociation on both the front and back surfaces of the globule, plus the evacuation of the central cavity.

5. SUMMARY

We have mapped the $\lambda 21$ cm continuum and H I emission at $\sim 1'$ resolution, covering the nearby (750 pc) H II region IC 1396, which contains a number of cometary globules with bright, ionized rims. A small number of globules have long comet-like “tails” of H I extending as much as $30'$ (8 pc), pointing away from the central ionizing star (HD 206267). The masses of these H I structures range from $\sim 4 M_{\odot}$ to $\sim 20 M_{\odot}$, which is a small fraction (less than 5%) of the molecular mass of the globules. The H I is blueshifted in velocity relative to the CO, as would be expected if the H I tails were material being accelerated away from the globules. However, there is little evidence for acceleration within the H I tails. There is sufficient momentum flux in the stellar wind originating from the central star to have accelerated this much material in a relatively short time. These observations are thus consistent with a scenario in which the globules are being ionized and photodissociated on the front surface by the central star, and the ablated material is then being blown away from the globule by the stellar wind after which it drifts into the shadow of the globule, to form the long comet-like tails of atomic hydrogen. An intriguing ringlike structure surrounding one globule is likely caused by ionization/dissociation of the front and back surfaces of the globule by two different stars.

This work represents the first results of the Galactic Plane Survey now underway at the Dominion Radio Astrophysical Observatory.

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ical Observatory is operated as a national facility by the Herzberg Institute for Astrophysics of the National Research Council of Canada. The Survey is supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

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