THE ROTATING MOLECULAR CORE AND PRECESSING OUTFLOW OF THE YOUNG STELLAR OBJECT BARNARD 1C

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ABSTRACT

We investigate the structure of the core surrounding the recently identified deeply embedded young stellar object Barnard 1c which has an unusual polarization pattern as traced in submillimeter dust emission. Barnard 1c lies within the Perseus molecular cloud at a distance of 250 pc. It is a deeply embedded core of 2.4 $M_\odot$ (Kirk et al.) and a luminosity of $4 \pm 2L_\odot$. Observations (and resolutions) of $^{12}$CO $J = 1 - 0$ (9.2$''$ $\times$ 5.9$''$), $^{13}$CO $J = 1 - 0$ and C$^{18}$O $J = 1 - 0$ (14.3$''$ $\times$ 6.7$''$), HCO$^+$ $J = 1 - 0$ (7.6$''$ $\times$ 5.8$''$), and N$_2$H$^+$ $J = 1 - 0$ (5.9$''$ $\times$ 4.6$''$) were obtained with the Berkeley-Illinois-Maryland Association array, together with the continuum at 3.3 mm (6.4$''$ $\times$ 4.9$''$) and 2.7 mm (9.5$''$ $\times$ 6.3$''$). The field of view of the BIMA array antennas at 3 mm is 2.1$''$. Single-dish measurements of N$_2$H$^+$ $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$ with FCRAO reveal the larger scale emission in these lines with resolutions of 57.5$''$ and 60.5$''$, respectively. The $^{12}$CO and HCO$^+$ emission traces the outflow extending over the full field of view, which coincides in detail with the S-shaped jet recently found in Spitzer IRAC imaging. The N$_2$H$^+$ emission, which anticorrelates spatially with the C$^{18}$O $J = 1 - 0$ emission, originates from a rotating envelope with effective radius $\sim 2400$ AU and mass $2.1 - 2.9 M_\odot$, as derived from the 3.3 mm continuum emission. N$_2$H$^+$ emission is absent from a 600 AU diameter region around the young star, offset from the continuum peak. The remaining N$_2$H$^+$ emission may lie in a coherent torus of dense material. With its outflow and rotating envelope, B1c closely resembles the previously studied object L483-mm, and we conclude that it is a protostar in an early stage of evolution, i.e., Class 0 or in transition between Class 0 and Class I. We hypothesize that heating by the outflow and star has desorbed CO from grains which has destroyed N$_2$H$^+$ in the inner region and surmise that the presence of grains without ice mantles in this warm inner region can explain the unusual polarization signature from B1c.

Subject headings: ISM: clouds — ISM: molecules — ISM: individual (Barnard 1) — stars: formation — radio lines: ISM

1. INTRODUCTION

Class 0 sources represent the youngest phase of low-mass star formation. They are characterized by higher infall rates than more evolved sources based on outflow activity (Bontemps et al. 1996; Whitworth & Ward-Thompson 2001), an absence of optical emission, and a high ratio of submillimeter to bolometric luminosity. Observations of the internal structure of Class 0 objects rely on interferometers because the sources remain deeply embedded within their parent molecular clouds. To understand the kinematics of the collapse process requires observation of multiple molecular lines because the chemistry within these dense, cold cores is complex. Carbon-bearing species are observed to be strongly depleted within the core interiors due to freeze-out onto grains. Nitrogen-bearing species were thought to deplete much more slowly than carbon-bearing species because of the low binding energy of the N$_2$ molecule, requiring long periods of time or very high densities to show depletion (Bergin & Langer 1997; Bergin et al. 2002). However, recent laboratory results indicate that CO binding energies are comparable to those of N$_2$. These studies also indicate that the degree of mixing of N$_2$ and CO ices impacts the desorption timescales (Oberg et al. 2005; Bisschop et al. 2005). Nonetheless, it is clear that N$_2$H$^+$ (and its daughter product NH$_3$) show a strong rise in abundance as its main destroyer, $^{12}$CO, depletes from the gas, making N$_2$H$^+$ an effective tracer of internal core kinematics (e.g., Aikawa et al. 2005). When $^{12}$CO is present however, reactions between C$^+$ or $^{12}$CO lead to the eventual destruction of the two standard nitrogen-bearing tracers.
Recent observations of several Class 0 sources have shown an absence of $N_2H^+$ emission at the source position on scales within several hundred AU of the protostar (i.e., Jørgensen, Schöier & van Dishoeck 2004). Typically, $N_2H^+$ emission is depressed at the core center and has been interpreted as destruction of $N_2H^+$ due to evaporation of CO and its isotopes from dust grains (e.g., L483-mm (hereafter L483), Jørgensen 2004 or depletion of $N_2H^+$ at high densities (e.g., IRAM 04191+1522 (hereafter IRAM 04191), Beloche, André, Despois & Blindec 2002). An absence of $N_2H^+$ cannot be purely an indicator of age; L483 is thought to be in transition between Class 0 and Class I (Tafalla et al. 2000) while IRAM 04191 is estimated to be among the youngest Class 0 sources known (André, Motte & Bacmann 1999). Interestingly, in both cases, the $N_2H^+$ emission morphology is double peaked around the center with a signature indicating rotation, and an anticorrelation is noted between $N_2H^+$ emission and the emission from tracers dominated by the outflow ($^{13}CO$ and HCO$^+$). However, in L483, $^{18}O$ is centrally peaked on the source indicating that $^{12}CO$ has been evaporated from dust grains at the core center. The combination of $N_2H^+$ and $^{18}O$ morphology could thus discriminate between whether an absence of $N_2H^+$ is due to depletion onto dust grains or the destruction of $N_2H^+$ in the presence of $^{12}CO$.

In this paper, we present observations of the internal structure of the protostellar core Barnard 1c (B1c) from the Berkeley-Illinois-Maryland Association (BIMA) array and the Five Colleges Astronomical Radio Observatory (FCRAO) 14 m telescope. B1c was discovered during 850 $\mu$m polarimetry mapping in Barnard 1 by Matthews & Wilson (2002). Recent IRAC imaging from Spitzer reveals that this source is highly reddened and deeply embedded in the B1 cloud with an extensive, highly collimated outflow (Jørgensen et al. 2004). The presence of central cavities within young protostellar cores is of particular relevance to B1c because a heated central region could explain why B1c has a unique signature in polarized emission. Its polarization pattern suggests that the polarized intensity rises to the center of the core (Matthews & Wilson 2002), rather than flattening out as seen in other cores. When compared to the total intensity, a flat distribution in polarized intensity produces a declining ratio toward the peaks of cores. All other low-mass starless and star-forming cores observed in polarized dust emission have a so-called “polarization hole” at high intensities, thought to arise from changes in magnetic field geometry or dust grain physics (Matthews 2005). One of the favored explanations for the polarization holes is that the grains at core centers are ineffective polarizers (due to changing grain physics). Heating removes the outer grain mantles and could increase the polarization efficiency of the grains within cavities (Whittet et al. 2001).

Barnard 1 is part of the Perseus molecular cloud complex (Bachiller & Cernicharo 1986) which is one of the closest star-forming regions to the Sun. Its distance is the subject of some debate, with estimates ranging from 200 pc (based on extinction studies, Cernis 1990) to 330-350 pc (based on the Per OB2 association, de Zeeuw, Hoogerwerf & de Bruijne 1999). The presence of central cavities within young protostellar cores (Jørgensen et al. 2006) and deeply embedded in the B1 cloud with an extinction of $250 \pm 50$ pc to the Barnard 1 cloud, as determined from recent estimates of extinction (Cernis & Stražys 2003) and measurements of parallax in members of IC 348 (Belikov et al. 2002).

This paper presents high resolution interferometric data from several molecular species and continuum emission at 2.7 and 3.3 mm. The main objective is to determine whether B1c exhibits a central cavity which could help explain its unique polarization properties. The observations and data reduction techniques are described in §2. We present the continuum results and derive the core mass in §3. The molecular line data are presented in §4. We discuss these data in §5. Our findings are summarized in §6.

2. OBSERVATIONS AND DATA REDUCTION

2.1. BIMA Interferometric Data

Observations were made over the period of 2002 October to 2003 April using the Berkeley-Illinois-Maryland Association (BIMA) interferometer (Welch et al. 1996) in Hat Creek, CA. We utilized a single pointing toward the position $\alpha_{2000} = 03^h33^m17^s.89, \delta_{2000} = +31^\circ06'33''0$ (J2000). Two configurations of the ten 6.1 m antennas were used to observe the lines of $N_2H^+ J = 1 - 0$ and HCO$^+ J = 1 - 0$. The C-array and B-array had projected baselines between 23-33 k$\lambda$ and 3-74 k$\lambda$, respectively. The $^{12}CO J = 1 - 0$ line and its isotopomers $^{13}CO J = 1 - 0$ and $^{18}O J = 1 - 0$ were observed only in the C-array configuration. Table 1 contains the sensitivities achieved per track.

The $N_2H^+ J = 1 - 0$ line was observed utilizing the digital correlator to record the line in bands of 6.25 and 12.5 MHz width with 256 channels each, giving resolution of 0.079 and 0.157 km s$^{-1}$. The larger bandwidth window permitted detections over the range of the seven hyperfine components of $N_2H^+ J = 1 - 0$. All 10 antennas were available for both 93 GHz tracks.

The HCO$^+ J = 1 - 0$ line was observed in bandwidths of 6.25 and 12.5 MHz with 256 channels each, resulting in resolutions of 0.082 and 0.164 km s$^{-1}$. A window in the upper side band was sensitive to $^{12}CO J = 2 - 1$ in a 12.5 MHz window with 0.085 km s$^{-1}$ resolution. Three tracks were obtained in the B array and two in the C array. All 10 antennas were available for three tracks, with one antenna offline for a B array track and two antennas missing from one of the C array tracks.

The $^{12}CO J = 1 - 0$ line was observed in a band 12.5 MHz wide across 256 channels. We also observed it in 100 MHz windows to detect high velocity CO gas. The velocity resolutions were 0.127 km s$^{-1}$ and 8.127 km s$^{-1}$, respectively. No CO emission was detected at velocities exceeding 20 km s$^{-1}$ from the rest velocity of the source. As for the $N_2H^+ J = 1 - 0$ phase, the phase calibrators were 3c84 and 0237+288. Only 9 of 10 antennas were
useable for this track due to phase incoherence on antenna 9. We were sensitive to the CN $J = 1 - 0$ line in the USB during this observation, but none was detected.

The $^{13}$CO $J = 1 - 0$ and C$^{18}$O $J = 1 - 0$ lines were observed with the digital correlator configured to record the lines in the upper side band with 12.5 MHz bandwidth over 256 channels. One antenna was offline during this track. Data from a second antenna was flagged due to the same phase problems. Spectral line data from a third antenna was removed due to noisy phases and amplitudes.

Phase and amplitude variations were calibrated by observing the nearby quasars 3c84 and 0237+288 (when 3c84 reached elevations exceeding 85°) approximately every 30 minutes. The adopted fluxes of these quasars were epoch dependent and measured against observations of the planet Uranus when possible. The calibration was performed using the MIRIAD (Multichannel Image Reconstruction, Image Analysis and Display; Sault, Teuben & Wright (1995)) task MSELFCAL. Absolute flux calibration was done using Uranus when observed or by derived fluxes of the gain calibrators during the same epoch as our observations (utilizing the catalogue of fluxes at "plot\_swiflux" on the BIMA website\(^1\)). Based on the uncertainty in flux of the calibrator and the relative variations in the flux of the quasar, we estimate our overall flux calibration is accurate to the 30% level.

Subsequent processing of the data, including the combination of data from different configurations, were done with MIRIAD. Images were produced using MIRIAD’s CLEAN algorithm and "robust" weighting (robustness parameter 0.2) of the visibilities to optimize the signal-to-noise and the spatial resolution. Resulting noise levels are 0.15 Jy/beam in 0.16 km s\(^{-1}\) channels for the N$_2$H\(^+\) $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$ line emission, 0.4, 0.6 and 1.0 Jy/beam in 0.13 km s\(^{-1}\) channels for the $^{13}$CO $J = 1 - 0$, C$^{18}$O $J = 1 - 0$ and $^{12}$CO $J = 1 - 0$ line emission respectively. The rms levels in the continuum maps are 6.8 and 4.0 mJy beam\(^{-1}\) for the continuum images at 2.7 and 3mm, respectively. The best naturally-weighted resolution is obtained for N$_2$H$^+$ $J = 1 - 0$, with a beam of FWHM of 5.9" × 4.6". Moderate resolution is obtained for HCO$^+$ $J = 1 - 0$ and $^{12}$CO $J = 1 - 0$ with FWHM of 7.6" × 5.8" and 9.2" × 5.9" respectively. Due to limited (u, v) coverage, the FWHM of $^{13}$CO $J = 1 - 0$ and C$^{18}$O $J = 1 - 0$ data is 14.3" × 6.7". Integrated-intensity and velocity-centroid images were obtained from the cleaned spectral-line cubes using a 1 or 2σ clip level. The resolution of the continuum images is 9.5" × 6.3" and 6.4" × 4.9" for 2.7 and 3.3 mm respectively.

\(^{22}\) FCRAO Data

To obtain information on large spatial scales, we observed B1c in N$_2$H$^+$ $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$ emission with the Five Colleges Radio Astronomical Observatory (FCRAO). The data were obtained in very good weather. We achieved an rms of 0.08 K (T$^*$) in 24 minutes on source. The N$_2$H$^+$ $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$ data were obtained simultaneously using the array SEQUOIA. The beamsize of the FCRAO data is 57.5" at 93.17378 GHz and 60.5" at 89.188523 GHz. The maps cover an area of diameter 12.5" centered on the contin-

\(^{1}\) http://bima.astro.umd.edu
uum peak of the BIMA array data.

2.3. Combination of Single Dish and Interferometer Data

For the HCO\(^+\) and N\(_2\)H\(^+\) data sets, we were able to combine the BIMA array and FCRAO data to obtain total power maps of each transition. We utilized the method described by Stanimirovic et al. (1999) to combine the data in the image plane.

The FCRAO data were reordered to match the BIMA axes (x,y,v), converted to main beam from antenna temperature, and rescaled to Janskys. The MIRIAD task REGRID was then used to regrid the FCRAO data to match the parameters of the BIMA array data cube. Slight differences in line frequencies were compensated for by a shift in the reference velocity of the FCRAO spectra prior to regridding. The shifts required were 0.885 and 0.016 km s\(^{-1}\) for N\(_2\)H\(^+\) \(J = 1\) − 0 and HCO\(^+\) \(J = 1\) − 0 spectra, respectively. In the latter case, the shift is significantly less than the width of individual channels. A map of the FCRAO beam for each transition was generated and truncated at the 5\% level, creating a mask applied to the appropriate single dish data cube. The weighting factor for the single dish map was determined by a ratio of the beam areas. The composite map was then created using a linear combination of the BIMA dirty map and the single dish map, followed by deconvolution using the combined beam (Stanimirovic et al. 1999).

3. DUST EMISSION TOWARD B1C

Figure 1 shows the continuum detections toward B1c at 3.3 and 2.7 mm. The source is located at \(\alpha_{\text{J2000}} = 03^h33^m17.878\), \(\delta_{\text{J2000}} = +31^\circ09'31''98\), which is the peak of the 3.3 mm emission. The 2.7 mm emission is poorly resolved with positive flux density detected to a radius of 13\". The 3.3 mm emission is better resolved with the core extending to 11\".

The continuum emission is not point-like; Figure 1 shows that it is extended to the northwest and the southeast of the continuum peak at both wavelengths. The continuum emission toward the southeast does not coincide at the two wavelengths, but in each case it is strong, exceeding 4\(\sigma\) at 3.3 mm at \(\alpha_{\text{J2000}} = 03^h33^m18.75\), \(\delta_{\text{J2000}} = +31^\circ09'21''71\), corresponding to 16.6 mJy beam\(^{-1}\). The 2.7 mm peak to the southeast also exceeds 3\(\sigma\) (21.7 mJy beam\(^{-1}\)) at \(\alpha_{\text{J2000}} = 03^h33^m20''20\), \(\delta_{\text{J2000}} = +31^\circ09'14''5\).

Figure 2 shows the visibility amplitude as a function of \((u,v)\) distance at each wavelength. Flux densities above the zero-sigma value (dashed lines) are found for only a few of the shortest \((u,v)\) distances and are generally marginal detections. Based on these plots, we interpret the continuum maps as spatially filtered observations of a resolved, extended envelope, similarly to the case of L483 (see Figure 2 of Jørgensen 2001). The poorer \((u,v)\) sampling at 2.7 mm leads to the recovery of less extended emission than we detect at 3.3 mm.

Using the MIRIAD task IMFIT, we have fit gaussians to the 2.7 mm and 3.3 mm maps, fixing the peak flux density and position of the peak emission. As Table 2 shows, the resultant total flux densities derived are higher than those obtained by use of aperture photometry. As expected from Figure 2, less flux is recovered at 2.7 mm than at 3.3 mm. However, the sizes measured for the core are remarkably similar at each wavelength. Based on the 3.3 mm deconvolved size, the scale of the detected inner envelope is \(\sim 3100 \times 1800\) AU at 250 pc. The effective radius of this central region \((r_{\text{eff}} = \sqrt{ab}\) where a and b are the major and minor axes, respectively) is \(\sim 2400\) AU. This is much smaller than the 12000 AU effective radius derived from the SCUBA map at 850 \(\mu\)m by Kirk, Johnstone & Di Francesco (2000). The measurement from the JCMT incorporates the entire outer envelope of B1c, to which our BIMA array data are not sensitive. It is normal to measure less flux in interferometric maps than in single dish data because interferometers preferentially sample structure on small scales. Therefore, our continuum estimates only apply to the inner envelope (i.e., not the region traced by the JCMT).

At 3.3 mm, it is possible that some continuum emission may be due to free-free emission instead of emission from dust. We have reduced an archival observation\(^2\) from the Very Large Array at 1.3 cm in which B1c lies just outside the primary beam. There is no detection of 1.3 cm emission in this map, and the 3\(\sigma\) upper limit is 3.7 mJy beam\(^{-1}\). Since the free-free emission is expected to be relatively flat, a contribution of this magnitude cannot be a significant source of the continuum emission at 3.3 mm.

3.1. Mass, Column and Density of the Inner Core

The mass of the continuum source is easily determined, assuming optically thin conditions, from the flux of the source and the temperature via the relation

\[M = \frac{F_{\nu} d^2}{\kappa_{\nu} B_{\nu}(T_d)}\]  

where \(F_{\nu}\) is the flux, \(d\) is the source distance, \(\kappa_{\nu}\) is the dust opacity and \(B_{\nu}(T_d)\) is the Planck function at temperature \(T_d\). Table 3 presents the masses calculated for our measured flux densities for different assumptions of \(\beta\) (and hence \(\kappa_{\nu}\)) and \(T_d\). Our continuum maps are spatially filtered and are not sensitive to the large scale emission of the core (i.e., the outer envelope). If this source is young, then much of the mass is expected to remain in the envelope; therefore, observations sensitive only to the inner envelope should be expected to yield masses smaller than that measured with a single dish telescope.

\(^2\) The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Molecular Line Study of Barnard 1c

Fig. 1.— Continuum emission from B1c at 3.3 mm and 2.7 mm. The respective beams are shown at the bottom right. The 3.3 mm contours are plotted at 2, 4, 6 and 8 $\sigma$ where $\sigma = 4.1$ mJy beam$^{-1}$. The 2.7 mm contours are at levels of 2, 3, 4, 5, and 6 $\sigma$ where $\sigma = 6.8$ mJy beam$^{-1}$.

TABLE 2

|               | 2.7 mm   | 3.3 mm   |
|---------------|----------|----------|
| Measured Peak Flux Density [mJy beam$^{-1}$] | 47.5 ± 14 | 39.0 ± 13 |
| Total Flux Density (aperture) [mJy]      | 71 ± 21  | 123 ± 37  |
| Total Flux Density (gaussian fit) [mJy]  | 89 ± 27  | 150 ± 50  |
| Size [$''$]         | 12.5 × 8.9 | 13.8 × 8.8 |
| PA [$^\circ$]       | −51      | −30       |
| Deconvolved size [$''$] | 10.2 × 1.6 | 12.3 × 7.2 |
| Deconvolved PA [$^\circ$] | −66      | −33       |

*Measured in apertures of 13$''$ and 11$''$ radius for 2.7 and 3.3 mm, respectively.

Fig. 2.— Plots of visibility amplitude versus projected baseline for our continuum datasets. Points are the amplitudes; the error bars are the formal standard deviations from the mean. The dotted line represents the signal expected from the noise. We have only a single track each at 109 and 115 GHz, both in the C array. This is reflected in the extremely limited ($u, v$) distance coverage. Those bins where the detected amplitude exceeds the value consistent with noise are even more limited. The coverage is much better at 3.3 mm, where we have multiple tracks at 89 and 93 GHz, in both the B and C arrays. Similarly, the range of projected baselines in which we detect signal well above those consistent with noise are also much more extended.

to 1.0 than to 1.5. For the same dust temperature as derived from single dish data (15 K) and $\beta = 1.0$, the mass of the inner envelope is $2.9 \pm 0.9 M_{\odot}$. For $T_d = 20$ K, the mass is $2.1 \pm 0.6 M_{\odot}$. Therefore, the mass of the inner core lies in the range $2.1 - 2.9 M_{\odot}$.

Here, we reiterate that our continuum data are hindered by excessive spatial filtering. This caveat prevents us from rigorously predicting values of $\beta$ or dust temperature in the inner core, since the BIMA flux densities are not easily compared either to each other or the existing single dish flux density from the JCMT.

Using the continuum flux, we can also estimate the column density of molecular hydrogen within the core using the relation:

$$N(H_2) = \frac{S_\nu}{\Omega_m \mu m_H \kappa_\nu B_\nu(T_d)}$$

where $S_\nu$ is the peak flux density, $\Omega_m$ is the main beam solid angle in steradians, $\mu$ is the mean molecular weight (2.33), $m_H$ is the mass of atomic hydrogen, $\kappa_\nu$ is the dust opacity per unit mass. Table contains estimates of the column density for different values of $\beta$ and $T_d$. At 3.3 mm, for a temperature of 20 K, the column density toward the peak is $(6.8 \pm 2.0) \times 10^{21}$ cm$^{-2}$, for $\beta = 1.0$. Conversion to extinction using $N(H_2)/A_V = 10^{21}$ cm$^2$/mag yields a visual extinction of $680 \pm 200$ mag to the central peak of the B1c core.

Assuming the inner envelope is as deep as it is wide,
TABLE 3
MASSES AND COLUMN DENSITIES FROM CONTINUUM FLUX DENSITY

| Temperature (K) | Mass (M⊙) | Column Density (10^{23} cm^{-2}) |
|----------------|-----------|----------------------------------|
| 12             | 1.0049    | 0.0049                           |
| 15             | 1.2 ± 0.4 | 1.75 ± 0.5                       |
| 20             | 0.92 ± 0.3| 1.32 ± 0.4                       |
| Column Density | 4.3 ± 1.3 | 6.2 ± 1.9                        |

*Derived from $\kappa_0(\nu_0/\nu)^{\beta}$ where $\kappa_0$ is calculated to be 0.01 cm^2 g^{-1} at $\nu_0 = 231$ GHz [Ossenkopf & Henning 1994].

Fig. 3.— Maps of integrated intensity in $^{12}$CO J = 1 − 0, $^{13}$CO J = 1 − 0, C^{18}O J = 1 − 0, HCO$^+$ J = 1 − 0, N$_2$H$^+$ J = 1 − 0 and SiO J = 2 − 1 toward the source Barnard 1c. (a) N$_2$H$^+$ J = 1 − 0 map shows the double-peaked distribution with peaks offset from the 3.3 mm continuum peak of (c), shown as a triangle. The N$_2$H$^+$ data are integrated over 21.2 km s$^{-1}$ (a range which contains all 7 hyperfine components); contours range from 2 to 10 $\sigma$ in steps of 2 $\sigma$ where $\sigma$ = 47 mJy beam$^{-1}$. Dashed contours show the corresponding negative contours. (b) C^{18}O J = 1 − 0 data clearly trace the core emission and are centrally peaked on the 3.3 mm continuum source peak (triangle). The C^{18}O data are uniform weighted for better resolution (11.7'' × 5.4'') and integrated over 2.1 km s$^{-1}$, and the contours range from 2 to 4 $\sigma$ in steps of 1 $\sigma$ = 0.17 Jy beam$^{-1}$. (c) SiO J = 2 − 1 data shows no significant detections. Contour levels are 2 and 3 $\sigma$ where $\sigma$ = 0.03 Jy beam$^{-1}$. (d) HCO$^+$ data are integrated intensity in greyscale and white contours; contours range from 2 to 8 $\sigma$ where $\sigma$ = 0.16 Jy beam$^{-1}$. Negative contours of the same range are also plotted. The HCO$^+$ map in greyscale and white contours are integrated over 17.2 km s$^{-1}$. The contours range from 2 to 6 $\sigma$ where $\sigma$ = 35 mJy beam$^{-1}$. (f) $^{13}$CO J = 1 − 0 integrated emission over 4.3 km s$^{-1}$ reveals no emission associated with the continuum peak (triangle). Contours range from 2 to 4 $\sigma$ in steps of 1 $\sigma$ = 75 mJy beam$^{-1}$. As in other plots, the dashed contours represent corresponding negative values.
then we can crudely estimate the central density by adopting the effective diameter as the depth and assuming a constant density sphere. Then the density is just the column density divided by the depth, and the central column density is \( (9.0 \pm 2.6) \times 10^6 \text{ cm}^{-3} \). A comparable calculation using 2.7 mm data yields the lower estimate of \( (3.3 \pm 1.0) \times 10^6 \text{ cm}^{-3} \). Reasonable estimates of the density therefore range from \( (3 - 9) \times 10^6 \text{ cm}^{-3} \).

4. MOLECULAR EMISSION TOWARD B1C

Maps of the integrated intensity of \( ^{12}\text{CO} \ J = 1 - 0 \), \( ^{13}\text{CO} \ J = 1 - 0 \), \( ^{18}\text{O} \ J = 1 - 0 \), \( \text{HCO}^+ \ J = 1 - 0 \), \( \text{N}_2\text{H}^+ \ J = 1 - 0 \), SiO \( J = 2 - 1 \) as detected by the BIMA array are presented in Figure 3. The outflow from B1c is prominently detected in \( ^{12}\text{CO} \ J = 1 - 0 \) and \( \text{HCO}^+ \ J = 1 - 0 \). The \( \text{N}_2\text{H}^+ \ J = 1 - 0 \), \( ^{18}\text{O} \ J = 1 - 0 \) clearly trace the envelope around the central source. The \( ^{13}\text{CO} \ J = 1 - 0 \) detections show no emission associated with the core, but may trace some compact features in the outflow. SiO \( J = 2 - 1 \) is not detected. The systematic velocity of the source is \( 6.35 \pm 0.02 \text{ km s}^{-1} \), based on a fit to the \( \text{N}_2\text{H}^+ \ J = 1 - 0 \) spectrum at the position of the continuum source.

4.1. The Core in \( \text{N}_2\text{H}^+ \) and \( ^{18}\text{O} \)

\( \text{N}_2\text{H}^+ \ J = 1 - 0 \) is strongly detected in B1c, indicating dense, cold gas within the core. Figure 3a shows that the integrated intensity of \( \text{N}_2\text{H}^+ \ J = 1 - 0 \) exhibits a double-peaked structure, with both peaks avoiding the position of the continuum source (indicated by the triangle) and the outflow, as shown in Figures 3a and 3b. In contrast, Figure 3b shows that the \( ^{18}\text{O} \ J = 1 - 0 \) emission is strongly centrally peaked very close to the continuum source position. Figure 3c shows a comparison of the distributions of the \( ^{18}\text{O} \) and \( \text{N}_2\text{H}^+ \) emission. The emission in a strip along the flattened axis of the core is also shown. This figure clearly illustrates the relative positions of the peaks in the \( ^{18}\text{O} \ J = 1 - 0 \) and \( \text{N}_2\text{H}^+ \ J = 1 - 0 \) emission. Despite our significantly poorer resolution in \( ^{18}\text{O} \ J = 1 - 0 \), the distribution is strikingly similar to that observed toward L483 (Figure 10 of Jørgensen 2004). The relative strength of the emission at each \( \text{N}_2\text{H}^+ \) peak is comparable, which differs from the results in L483, in which one peak was noticeably brighter than the other.

This morphology is seen across a wide range of young protostellar objects. It is very similar to that observed by Jørgensen 2004 in the more luminous (9L⊙) evolved Class 0 source L483, and is also seen in NGC1333 IRAS 2 (Jørgensen et al. 2004a) and sources in the Serpens molecular cloud (Hogerheijde 2005). It is also noted in the very low luminosity object (VeLLO) IRAM 04191 (0.15L⊙, Lee, Ho & White 2003). In B1c, the \( \text{N}_2\text{H}^+ \) emission is not confined merely to the two peaks, but extensions are detected to the east and southeast which bound the outflow emission in \( ^{12}\text{CO} \) and \( \text{HCO}^+ \). These extensions could be the dense edges of a conical cavity carved into the envelope by the molecular outflow, as depicted in our schematic diagram of the source (see Figure 4). The projected opening angle of this cavity is \( \sim 55^\circ \), based on the lowest contour of the eastern extensions of \( \text{N}_2\text{H}^+ \) emission in the integrated intensity images (Figure 3d) relative to the position of the continuum source. The uncertainty on the opening angle of the cavity is \( \sim 10^\circ \).

A third extension in \( \text{N}_2\text{H}^+ \) is observed to the northwest along the 3σ contours of the \( \text{HCO}^+ \) and \( \text{CO} \) emission. No \( \text{N}_2\text{H}^+ \) is detected along the other edge of the red-shifted outflow emission in the integrated intensity map.
The detected $^{12}$CO and $^{18}$O $J = 1 - 0$ emission exhibits a bipolar morphology with the blue lobe emission to the southeast much stronger than the red lobe emission to the northwest. Significantly, some $^{12}$CO $J = 1 - 0$ emission is also detected coincident with the central core, but HCO$^+$ $J = 1 - 0$ is not detected toward the position of the continuum source. As observed in L483 by Jørgensen et al. (2004a), the N$_2$H$^+$ data is anticorrelated with the HCO$^+$ emission.

The zeroth moment of $^{12}$CO and C$^{18}$O data are compared in Figure 6. The C$^{18}$O $J = 1 - 0$ emission is highly centrally peaked on the continuum source and is absent along the outflow axis, due to it relatively low abundance. The $^{12}$CO $J = 1 - 0$ outflow appears to have carved out the lower density envelope traced by C$^{18}$O $J = 1 - 0$ (integrated over the central velocities associated with the source) in a similar manner as the very dense gas traced by N$_2$H$^+$ $J = 1 - 0$ in Figure 6. In fact, the optically thin species C$^{18}$O $J = 1 - 0$ traces well both the continuum peak and small scale structure within the inner envelope, detected on the edge of the $^{12}$CO $J = 1 - 0$ emission along both the blue and red lobes. This is consistent with the findings of Arce & Sargent (2000) in their survey of outflow sources with the Caltech Millimeter Array. The orientation of the outflow from B1c is approximately $-55^\circ$ east of north. Based on the blue lobe, the opening angle appears to be $\sim 35^\circ$ in projection. Figure 6 also clearly indicates the presence of red-shifted CO emission at the leading edge of the blue lobe.

4.2. The Outflow in HCO$^+$ and $^{12}$CO

The molecular outflow is clearly seen in both $^{12}$CO $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$, as shown in Figure 6. We did not detect any SiO $J = 2 - 1$ emission as shown by Figure 6. The detected $^{12}$CO $J = 1 - 0$ and HCO$^+$ $J = 1 - 0$ emission exhibits a bipolar morphology with the blue lobe emission to the southeast much stronger than the red lobe emission to the northwest. Significantly, some $^{12}$CO $J = 1 - 0$ emission is also detected coincident with the central core, but HCO$^+$ $J = 1 - 0$ is not detected toward the position of the continuum source. As observed in L483 by Jørgensen et al. (2004a), the N$_2$H$^+$ data is anticorrelated with the HCO$^+$ emission.

The zeroth moment of $^{12}$CO and C$^{18}$O data are compared in Figure 6. The C$^{18}$O $J = 1 - 0$ emission is highly centrally peaked on the continuum source and is absent along the outflow axis, due to it relatively low abundance. The $^{12}$CO $J = 1 - 0$ outflow appears to have carved out the lower density envelope traced by C$^{18}$O $J = 1 - 0$ (integrated over the central velocities associated with the source) in a similar manner as the very dense gas traced by N$_2$H$^+$ $J = 1 - 0$ in Figure 6. In fact, the optically thin species C$^{18}$O $J = 1 - 0$ traces well both the continuum peak and small scale structure within the inner envelope, detected on the edge of the $^{12}$CO $J = 1 - 0$ emission along both the blue and red lobes. This is consistent with the findings of Arce & Sargent (2000) in their survey of outflow sources with the Caltech Millimeter Array. The orientation of the outflow from B1c is approximately $-55^\circ$ east of north. Based on the blue lobe, the opening angle appears to be $\sim 35^\circ$ in projection. Figure 6 also clearly indicates the presence of red-shifted CO emission at the leading edge of the blue lobe.

4.2.1. Spitzer Mid-infrared Emission

Figure 6 shows the outflow emission from the source B1c as imaged by Spitzer with IRAC at 4.5 $\mu$m and the $^{12}$CO outflow emission from the BIMA array. The IRAC 4.5 $\mu$m band has been found to be a strong tracer of outflows which is likely due to the presence of H$_2$ pure rotational transitions and the CO fundamental vibrational mode within the bandpass (Noriega-Crespo et al. 2004). The outflow clearly extends for several arcminutes on either side of the driving source, B1c. The 4.5 $\mu$m emission is a strong tracer of molecular hydrogen, typically associated with protostellar jets. An “S-shaped” morphology is evident in the Spitzer map. Such S-shaped jets are interpreted as precession of the jet because of the presence of an (unseen) binary (e.g., Hodapp et al. 2005). Near the source, the outflow appears quite symmetric; however, at larger distances, the blue lobe widens while the red lobe appears to either split into two separate sequences of “bullets” or be confused with an outflow from a different source. The projected linear extent of the outflow detected by Spitzer is dependent on which distance one adopts to the Barnard 1 cloud. At 250 pc, the 6'' extent of the blue lobe from the central source indicates a distance of $\sim 90000$ AU, or 0.44 pc.

Comparison of the Spitzer data with the BIMA array data illustrates that the 4.5 $\mu$m emission lies along the central axis of the CO outflow very near the driving source. Like the molecular hydrogen emission, there is a bend in the $^{12}$CO emission, located precisely where the CO emission transitions from blue-shifted to red-shifted emission. We are constrained by the single pointing of the BIMA observations to a single primary beam of coverage in the CO emission. More extended $^{12}$CO $J = 1 - 0$ measurements are needed to compare the morphology of the molecular hydrogen (the driving jet) to the morphology of the entrained gas mapped by the $^{12}$CO. It is interesting that the position of the Spitzer emission peaks are anti-correlated with the CO peaks in the BIMA data, which is likely due to the difference in excitation conditions between the H$_2$ transitions that sample warm (few
hundred K) gas along the jet shocks and $^{12}$CO $J = 1 - 0$ which preferentially traces entrained, cold ($\sim 10$ K) gas.

4.3. $^{13}$CO $J = 1 - 0$ Emission

Figure S shows the integrated emission detected from $^{13}$CO $J = 1 - 0$. In contrast to the other CO isotopologues, the $^{13}$CO data do not clearly trace the core or the outflow. This is likely due to missing short spacings in the interferometric map which limit the sensitivity of this observation both to structure and emission. The peaks detected in $^{13}$CO may be associated with the outflow or the walls of a cavity carved by the outflow.

4.4. Moment Maps of the Core and Outflow

We produced moment maps of the combined N$_2$H$^+$ $J = 1 - 0$ emission from the FCRAO and BIMA array datasets over a velocity range of 1.57 km s$^{-1}$, or 10 channels. After creating the moment maps, we masked out all data values in the moment zero and moment one maps at positions with values less than 0.24 Jy beam$^{-1}$ km s$^{-1}$ in the moment zero map, which is approximately 1.5 times the rms level per channel, 0.14 Jy beam$^{-1}$.

Figure S shows the first and zeroth moments of the combined N$_2$H$^+$ $J = 1 - 0$ emission. The velocity gradient suggests that the molecular core is rotating about an axis aligned with the outflow. As in the integrated intensity map from the BIMA array of Figure S, the zeroth moment map of the combined dataset illustrates a double-peaked distribution with peaks offset from the position of the continuum emission. This morphology is expected from the projection of a torus of dense gas surrounding the core center (see Figure S). We similarly interpret this double-peaked feature as a rotating torus with the blue-shifted emission lying predominantly to the north and the red-shifted emission lying to the south as indicated by fits to the spectra and the features of the first moment map. Figure S shows the moment one map in greyscale and the moment zero map in contours. We have taken a position-velocity cut along the plane of the torus (through the continuum peak position and the two N$_2$H$^+$ $J = 1 - 0$ peaks) as shown in Figure S using the Karma program “kpvslice” (Gooch 1996). Figure S shows the PV emission of the isolated N$_2$H$^+$ $J = 1 - 0$ component. The emission is continuous across the molecular core, but emission peaks are well separated in velocity space. They are symmetric about the velocity of the source for this HFS component ($-1.64$ km s$^{-1}$). The distribution of the emission is very narrow in velocity space, limited to only a few velocity channels. Nonetheless, there is a clear velocity gradient across the core with a discernible shift in the centroid velocity across the two off-center peaks.

4.5. Kinematics of the Core and Outflow

4.5.1. Position-Velocity Diagrams

We have taken a position-velocity cut along the plane of the torus (through the continuum peak position and the two N$_2$H$^+$ $J = 1 - 0$ peaks) as shown in Figure S using the Karma program “kpvslice” (Gooch 1996). Figure S shows the PV emission of the isolated N$_2$H$^+$ $J = 1 - 0$ component. The emission is continuous across the molecular core, but emission peaks are well separated in velocity space. They are symmetric about the velocity of the source for this HFS component ($-1.64$ km s$^{-1}$). The distribution of the emission is very narrow in velocity space, limited to only a few velocity channels. Nonetheless, there is a clear velocity gradient across the core with a discernible shift in the centroid velocity across the two off-center peaks.
Fig. 7.— IRAC Spitzer data at 4.5 µm from Jørgensen et al. (2006) are compared to moment maps of the $^{12}$CO $J = 1 - 0$ emission over the blue and red lobes. The correlation between the position angle and central axis of the outflow is excellent between the near-IR and millimeter data. The inset shows the larger scale extent of the molecular hydrogen emission seen from Spitzer. $^{12}$CO $J = 1 - 0$ contours are from 3-10 Jy beam$^{-1}$ km s$^{-1}$, in steps of 1 Jy beam$^{-1}$ km s$^{-1}$. The cross marks the continuum peak of the BIMA data. The large circle indicates primary beam of a BIMA antenna.

Fig. 8.— First (greyscale) and zeroth (contour) moment maps from the combined FCRAO and BIMA array observations of $N_2H^+$ $1-0$ emission. The contours are intervals of 0.5σ from 1.5 to 6σ where $σ = 0.115$ Jy beam$^{-1}$ km s$^{-1}$. The cross marks the position of the continuum peak. These maps are taken over the single isolated component of the $N_2H^+$ hyperfine transitions, $F_1, F = 0.1 \rightarrow 1.2$. The white dashed line represents the slice taken to produce the position vs. velocity diagram of Figure 11, and defines the orientation of the “torus” at 10° east of north. The dot-dashed line represents the position angle of the outflow (-55° east of north) as measured from IRAC 4.5 µm and BIMA $^{12}$CO $J = 1 - 0$ data (see § 4.2).

Figure 10 shows that the strongest blue shifted emission is detected close to B1c. At larger distances from the source, the HCO$^+$ $J = 1 - 0$ emission is dominated by velocities closer to that of the source.

4.5.2. Spectra

Figure 13 shows the distribution of spectra (spatially binned to an area comparable to the beam size) across the core in the combined FCRAO and BIMA data. Fits to the hyperfine components of the $N_2H^+$ spectra were done using the CLASS software’s “hfs” fitting routine Buisson et al. 2002 with up-to-date weights and frequencies Dore et al. 2003. These fits were used to determine LSR velocities ($V_{LSR}$), intrinsic line widths ($Δv$), total optical depths ($τ_{tot}$), and excitation temperatures ($T_{ex}$). The distribution of line strengths is very atypical for $N_2H^+$. The hyperfine ratio suggests that the central velocity components should be strongest when compared to higher and lower clusters of hyperfine components. In B1c, the central component is often the same strength as the higher velocity component, which is indicative of high opacity or self-absorption of the brightest component. Solutions to the hfs fitting were not substantially improved by using only the outer triplet and the isolated component of the seven hyperfine lines to produce fits to the data for the LSR velocity and the linewidth; therefore, the fits shown in Figure 13 are all for the fits derived with all seven components.

All seven hyperfine components from the combined data were fit simultaneously in CLASS. We spatially binned the data onto a grid with spacing 5″ in R.A., and 6″ in declination. The fits reflect centroid velocities ranging from 5.94 to 6.68 km s$^{-1}$. The range of realistic line widths (FWHM) is ~ 0.3 to 1.5 km s$^{-1}$. The source velocities are systematically bluer to the north and redder to the south as has been discussed in § 4.4.

Figure 14 shows the distribution of $V_{LSR}$, $ΔV$ and line opacity (sum of the peak optical depths for all seven hyperfine components) across the core on the same grid as shown in Figure 13. The gradient in $V_{LSR}$ is well defined across the field. Higher values of $ΔV$ are observed along the outflow axis where the cavity has been carved in $N_2H^+$ emission than across the central core where linewidths are quite uniform. Some of the best fit solutions (assuming a single excitation temperature
Fig. 9.— Comparison of the zeroth moment \( N_2H^+ \) \( J = 1 - 0 \) emission on large scales from FCRAO, the BIMA array and combined FCRAO and BIMA array data, where the latter two maps have been convolved to the FCRAO beam size of 57.5″, shown at the top left of the FCRAO image. These maps are taken over all seven hyperfine components. The contours of the FCRAO and combined maps are at intervals of 10σ from 20 to 100σ where \( \sigma = 1.7 \text{ Jy beam}^{-1} \text{ km s}^{-1} \). The BIMA array map has substantially less flux than either the FCRAO or combined maps. The contours plotted range from 4 to 12 Jy beam\(^{-1} \text{ km s}^{-1}\), in steps of 4 Jy beam\(^{-1} \text{ km s}^{-1}\). A cross marks the position of the 3 mm source. The BIMA array data, convolved to a similar beam, peaks at the same position as the FCRAO data alone.

Fig. 10.— Upper panel: Moment zero maps of HCO\(^+\) (greyscale) and \( N_2H^+ \) (contours) show the displacement between the HCO\(^+\) and \( N_2H^+ \) emission. The HCO\(^+\) emission is confined to a cavity carved into the dense gas by the outflow. Contour levels are 2 to 6σ in steps of 0.5σ where \( \sigma = 0.11 \text{ Jy beam}^{-1} \text{ km s}^{-1} \). The dashed line shows the position of the position-velocity slice taken through the outflow (see Figure 12). Lower Panel: The first (greyscale) and zeroth (black contours) moment maps of HCO\(^+\) 1-0 emission from the B1c outflow. In the combined map of FCRAO and BIMA data, the blue lobe of the outflow remains brighter than the red lobe. The white contours show the moment zero \( N_2H^+ \) emission.

for all components) shown in Figure 13 produce very large total optical depths for the northern and southern emission peaks. These values indicate that at least one component is very optically thick and all components may be optically thick. Attempts to fit the spectra with lower, fixed estimates of \( \tau(\text{tot}) \) do an increasingly poor job of fitting the heights of the components. The software's minimum measurable optical depth is 0.1; in these instances, the emission must be optically thin, but we cannot discriminate between values of \( \tau(\text{tot}) \) lower than 0.1. The maximum value yielded is 30, obtained when components have equal strength.

Figure 14 shows only the isolated component of the \( N_2H^+ \) spectra, with a velocity range limited to -4 to 0 km s\(^{-1}\). These spectra reveal differences both in the peak of the lines and in line shape across the core, with some positions exhibiting a dip in the center of the line profile, which could indicate that even this line may be optically thick. It is also obvious that regions of poorer S/N produce poorer fits, higher (likely unphysical) estimates of \( \tau \).

TABLE 4

| Parameters Derived from \( N_2H^+ \) hfs fitting |
|---------------------------------------------|
| \( V_{\text{lsr}} \) [km s\(^{-1}\)] | 6.31 | 2.34 | 5.94 | 6.75 |
| \( \Delta V \) [km s\(^{-1}\)] | 0.61 | 0.37 | 0.26 | 1.85 |
| \( \tau(\text{tot}) \) | 6.99 | 8.37 | 0.100 | 30.0 |

\( a \) The maximum and minimum solutions for \( \tau(\text{tot}) \) based on the hfs routine are 0.1 and 30 respectively. Values of 0.1 indicate all components are optically thin, while 30 indicates that the component strengths are equal.

5. DISCUSSION

5.1. Column Density and Chemistry
5.1.1. Column Density of $N_2H^+$

In order to estimate the $N_2H^+$ column density, we require estimates of the FWHM of the lines and estimates of the line opacity. Figure 14 shows the distribution of line widths and opacities derived from the $N_2H^+$ $J = 1 - 0$ spectra. We derived the $N_2H^+$ column density using a simple curve of growth determined by assuming LTE excitation conditions at $T_{ex} = 12$ K, a line width of $0.75$ km s$^{-1}$, and the RADEx escape probability code$^3$ (Schoier & van der Tak 2005). This simple approach takes into account line opacity, but a more detailed envelope model with proper density and temperature slope will be required to get more accurate estimates (Matthews et al. in preparation). Figure 16 shows the column density distribution of $N_2H^+$ $J = 1 - 0$ emission in B1c. Since the LTE analysis predicts opacities on the order of unity while the spectra and its component fitting suggest significantly higher opacities, it is likely that the excitation is not in LTE (i.e., $T_{ex} < 12$ K). However, Figure 16 is illustrative as it shows the same depression in $N_2H^+$ emission seen in the zeroth moment map of Figure 17.

5.1.2. Column Density of $C^{18}O$

To derive the density at the core center, we estimate the column density at the peak of $C^{18}O$ $J = 1 - 0$ emission. We can derive the column density from the expression

$$N_{C^{18}O} = \frac{3.34\times10^{14}}{\nu \mu^2} \left(1 - \exp\left(-\frac{h\nu}{kT_{ex}}\right)\right)$$

$$\times \frac{\int T_{MB}dv}{\exp\left(-\frac{h\nu}{2kT_{ex}}\right) - 1 - \exp(-\tau)}$$

where $\nu$ is the frequency in GHz (109.78217 GHz), $\mu$ is the dipole moment in Debye (0.11 Db), $T_{ex}$ is the excitation temperature, and $J$ is the lower rotational level for the transition. We assume $T_{kin} = T_{ex}$ which is constant for all rotational levels, LTE is valid for the $C^{18}O$ gas and that the optical depth effects are completely accounted for by the factor $\tau/(1 - e^{-\tau})$. We evaluate the integral over the line width from the peak of the moment zero map, integrated over a linewidth of 1 km s$^{-1}$. We estimate $\tau$ from the peak temperature of the line via the expression

$$T_{peak} \approx \frac{h\nu}{k} \frac{1 - \exp(-\tau)}{\exp(h\nu/kT_{kin}) - 1}$$

where $T_{kin}$ is the kinetic temperature. From the spectrum at the peak position, we evaluate $\tau$ for $T_{peak} = 2$ K and $T_{kin} \approx T_{ex} = 12$ K. We find $\tau = 0.244$, which is consistent with the $C^{18}O$ emission being optically thin. The strength of the emission at the peak is 1.16 Jy beam$^{-1}$ km s$^{-1}$. Using the conversion factor for our BIMA array synthesized beam at 109 GHz (1.12 K/Jy beam$^{-1}$), $\int T_{MB}dv$ is 1.3 K km s$^{-1}$. Substitution of these values in equation 3 yields a column density of $1.03\times10^{15}$ cm$^{-2}$ (the uncertainty, based largely on the flux calibration, is $\sim 30\%$). Utilizing the abundance ratio $[C^{18}O]/[H_2] = 1.7 \times 10^{-7}$ (Prerking, Langer & Wilson 1982) yields an $H_2$ column density of $1.75 \times 10^{22}$ cm$^{-2}$. The effective radius of the beam in the $C^{18}O$ observation is $1.8 \times 10^{16}$ cm. Assuming the core is as deep as it is wide, the density at the peak is $\sim 9.5 \times 10^{5}$ cm$^{-3}$. This value is three times the estimated central density of $3.2 \times 10^5$ cm$^{-3}$ from the analysis of dust emission maps by Kirk, Johnstone & Di Francesco (2006), but a magnitude less than the estimate based on 3.3 mm continuum data in Figure 8. The difference is partly attributable to the different spatial filtering between the observations. The 2.7 mm data, with more comparable $(u, v)$ coverage to the $C^{18}O$ data, yields densities of $(3.3 \pm 1.0) \times 10^6$ cm$^{-3}$, closer to the value derived above.

Aside from the uncertainties introduced by the different degrees of spatial filtering, the discrepancy between the $H_2$ column density measured with dust and $C^{18}O$ most likely arises due to depletion from standard ISM abundances, leading to underestimates of $N(H_2)$. Although the grains must be heated in B1c due to the centrally peaked distribution of $C^{18}O$, some of the gas could remain frozen onto the dust grains. Assuming the dust represents the total column of the inner envelope and the gas is depleted, then the $[C^{18}O]/[H_2]$ ratio is $1.7 \times 10^{-7}$ but instead $1.3 \times 10^{-8}$ (from 2.7 mm dust continuum), a factor of 13 less. This value is similar to the values measured in Class 0 sources by Jørgensen, Schoier & van Dishoeck (2002).

5.2. A Depression in $N_2H^+$ Emission near the Core Center

As demonstrated by the integrated intensity and moment maps, the $N_2H^+$ emission is diminished near the core’s center. We are able to produce a more coherent picture of the central “cavity” in $N_2H^+$ emission by reweighting the $N_2H^+$ data presented in Figure 5 to uniform when creating the maps. The downweighting of shorter baselines degrades the S/N of the individual channels significantly, but the moment map produced retains high signal by utilizing all seven hyperfine components. Figure 14 shows the moment zero map produced from the uniformly weighted BIMA array data combined with FCRAO data. A high threshold ($3\sigma$) was placed on inclusion of individual channels into the moment map.

\footnote{www.strw.leidenuniv.nl/~moldata}
to avoid channels between components. The cross marks the position of the continuum source, and the triangle represents the pointing center of the JCMT observations presented in Matthews & Wilson (2002). The ring depicts the 14″ beam of the JCMT. The scale of the evaporated cavity is such that it would not have been resolved by the JCMT. The scale of the cavity is 2.7″ × 2.15″, at a position angle of 7°. This corresponds to 675 × 540 AU at a distance of 250 pc.

The depression of N$_2$H$^+$ emission in the inner envelope and along the outflow path is likely due to the destruction of N$_2$H$^+$ by molecules that are released from grains, most notably CO and H$_2$O. Chemical models of an evolving core with a central luminosity source (i.e., Class 0) suggest that by $10^5$ years a cavity of $\sim$ 700 AU will be seen in the N$_2$H$^+$ abundance and emission [Lee et al. 2004]. This is the direct result of stellar heating providing enough energy to evaporate CO from grains within the core center. This model may not be directly applicable to B1c due to differences in masses and/or luminosity, but it provides a rough estimate of the time that has passed since stellar ignition. In addition, observations and models suggest that N$_2$H$^+$ will also be destroyed within the outflow [Bachiller et al. 2001, Bergin et al. 1998], and we see a strong anticorrelation between the depression of emission and the presence of N$_2$H$^+$.

A central depression in N$_2$H$^+$ emission has also been detected in the transition Class 0/I source L483 by Jørgensen (2004) and in the low luminosity object IRAM 04191 by Belloche & Andrés (2004). Lee, Ho & Whitt (2005) estimate the inner edge of the IRAM 04191 cavity has a mean radius of 1400 AU. This is a factor of four times larger than the cavity detected in B1c. In a simple model where cavities grow over time, this suggests that B1c could be even younger than IRAM 04191’s estimated age of $3 \times 10^4$ yr since the onset of accretion [André, Motte & Bacmann 1999]. The gradients and line widths measured in N$_2$H$^+$ $J = 1 - 0$ are strikingly similar in these two cores, indicating strong dynamical similarities, although we stress that IRAM 04191 is one of the new Class of very low luminosity objects (VeLLOs, Di Francesco et al. 2006, Young et al. 2004) while B1c is a relatively luminous ($4 \pm 2 L_\odot$) Class 0 object (Matthews et al. 2006, in prep).

We can estimate a kinematic age for this source based on the outflow data. The projected linear extent of the outflow coupled with the distance from the source yields estimates of the source age. Using the brightest peak of
Fig. 14.— Distribution of derived values of $V_{LSR}$, linewidth and total optical depth based on the fits shown in Figure 13. The gradient across the source is obvious in the derived values of $V_{LSR}$. The linewidths are broader along the direction of the outflow and are narrower along the plane of the torus detected in integrated intensity. The optical depths show a large range of values from optically thin to very optically thick ($\tau \gg 1$), indicating that several hfs components may be optically thick. Table 3 shows the mean values of the parameters derived from the fits to Figure 13.

the blue lobe detected in $^{12}\text{CO} \ J = 1 - 0$ and assuming an inclination angle of 45°, the dynamical age is $3.7 \times 10^4$ yr, comparable to that of the source IRAM 04191 in Taurus ($3 \times 10^4$ years). To produce an age on the order of $10^5$ years, the outflow inclination angle must be $\sim 15^\circ$ (i.e., the outflow must lie almost along the line of sight).

The absence of $\text{N}_2\text{H}^+$ in IRAM 04191 is attributed to depletion within the cold core interior (Belloche, André, Despois & Blinder 2002). The strong centrally peaked detection of $^{18}\text{O} \ J = 1 - 0$ emission from B1c (see Figure 6) shows that depletion is not significant in B1c, and the anticorrelation between $\text{N}_2\text{H}^+$ with the core center and outflow lobes suggests that $\text{N}_2\text{H}^+$ is absent due to destruction by CO. In addition, the strong outflow detected with Spitzer (Figure 7) is highly collimated, suggestive of a young source, but its spatial extent suggests that the collapse of the driving source may not have been as recent as that in IRAM 04191. These characteristics are similar to those of L483 which is thought to be in transition to a Class I object (Tafalla et al. 2000).

Lee, Ho & White (2005) note that the centers of the molecular outflow and envelope surrounding IRAM 04191 are offset from the continuum source by approximately 560 AU. They suggest that the two cavities seen to the south of that source could be due to a binary in which one companion is too young to have any appreciable dust emission. There is also evidence for binarity within B1c, particularly in the behavior of its outflow (§4.2), which shows evidence of precession. The cavity center is also offset from the continuum source position.

There is as yet no detection of a second dust peak nor a second outflow in B1c.

5.3. Rotational Support

The observed global rotation velocities within the B1 cloud are insufficient to support the cloud against collapse by a factor of $\sim 8$ (Bachiller et al. 1990). The ages of embedded but optically visible objects LkHα 327 and LkHα 328 are between $4-6 \times 10^6$ yr (Cohen & Kulkarni 1979). Based on this, Bachiller et al. (1990) conclude that another mechanism must be providing substantial support to the B1 cloud. Within B1c, the two peaks of the rotating torus can be used to derive the rotational energy relative to the $V_{LSR}$ at the core center of B1c itself.

The inner edges of the torus are offset from the position of the continuum peak. For a sphere, the rotational energy is given by

$$E_{\text{rot}} = \frac{2}{5} \rho \ V \ v_r^2$$  \hspace{1cm} (5)$$

where $\rho$ is the mean density, $V$ is the volume, and $v_r$ is the radial velocity relative to the center. Based on estimates of the central density with $^{18}\text{O}$ (§5.1.2) and dust emission (Kirk, Johnstone & Di Francesco 2000), we adopt a mean density of $5 \times 10^5$ cm$^{-3}$ for B1c.

The radial velocity of the two peaks relative each other is $\sim 0.06$ km s$^{-1}$ (as derived from Figure 13). Thus, we estimate the radial velocity relative to the core center to be a relatively small shift of $\sim 0.03$ km s$^{-1}$. The mean offset of the peaks from the core’s velocity center is $\sim 4^\prime\prime$, or 1000 AU (for $d = 250$ pc), encompassing a volume of $1.4 \times 10^{49}$ cm$^3$. Thus, based on equation (5), the rotational energy of the core is $\sim 1.2 \times 10^{39}$ ergs.

Matthews & Wilson (2002) derived the energetics of the B1c core based on estimates of the magnetic field.
Fig. 15.—$^{12}$CO $J = 1-0$ and HCO$^+ J = 1-0$ which has carved a conical cavity into the envelope of B1c, destroying $^{12}$CO. The prominence of the outflow driven by this source is also evident in Spitzer IRAC data recently published by Jørgensen et al. (2006). Comparison of the CO molecular outflow and 4.5 μm data reveals that positions of changes in jet direction are mirrored by changes in velocity in the CO emission.

6. SUMMARY

Utilizing interferometric and single dish millimeter data from the BIMA array and FCRAO, we have probed the structure of the envelope of the source Barnard 1c in Perseus. We detect a powerful molecular outflow in $^{12}$CO $J = 1-0$ and HCO$^+ J = 1-0$ which has carved a conical cavity into the envelope of B1c, destroying $^{12}$CO. The prominence of the outflow driven by this source is also evident in Spitzer IRAC data recently published by Jørgensen et al. (2006). Comparison of the CO molecular outflow and 4.5 μm data reveals that positions of changes in jet direction are mirrored by changes in velocity in the CO emission.

We have detected significant $^{12}$CO $J = 1-0$ emission from B1c. Data from FCRAO reveal $^{12}$CO emission is of comparable scale to single dish dust continuum maps. High resolution data (created by uniform weighting of the BIMA data combined with the FCRAO data) reveal clearly a small cavity in which dense gas has been destroyed, most likely by heating by the outflowing gas.
Section 4.4. The cavity offset from the continuum peak position. B1c shows N\(^2\)H\(^+\) emission offset to the west of N\(^2\)H\(^+\) emission from B1c with a central cavity carved out by the outflow and heating by the central source. We argue the heating has released \(^{12}\)CO and its isotopes from grains near the central source, destroying N\(^2\)H\(^+\). N\(^2\)H\(^+\) survives in the rest of the inner envelope, as indicated by the torus (or pseudodisk) and the N\(^2\)H\(^+\) emission which brackets the outflow as traced in \(^{12}\)CO \(J = 1 - 0\) and HCO\(^+\) \(J = 1 - 0\). As is the case in L483, the double peaks of N\(^2\)H\(^+\) (torus) do not lie orthogonal to the outflow orientation. In B1c, the offset is \(\sim 65^\circ\).

Existing polarimetry data (Matthews & Wilson 2002), interpreted in the case of a constant field orientation through the core would indicate a magnetic field direction roughly parallel to the outflow orientation. As yet, there is no estimate of the field strength within B1c itself; however, using the estimate from the surrounding B1 cloud (Matthews & Wilson 2002) and the model of Galli & Shu (1993), the source age is estimated to have a lower limit of \(1.8 \times 10^4\) yr. The dynamical age estimate of \(3.7 \times 10^4\) yr is highly dependent on the inclination of the outflow.

In our forthcoming paper (Matthews et al., in preparation), we will present higher transition observations of \(^{12}\)CO and C\(^{18}\)O from the B1c outflow, as well as measurements of the 1.3 mm continuum from the SubMillimeter Array. With existing data, and new data from IRS on Spitzer, we will generate the spectral energy distribution and use it to constrain models of \(T(r)\) and \(\rho(r)\) which was not possible based on the weak continuum detections reported here.

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**Fig. 16.** Column density distribution of N\(^2\)H\(^+\) \(J = 1 - 0\) emission in B1c. Contours are sum of the N\(^2\)H\(^+\) \(J = 1 - 0\) emission over all channels with signal exceeding 3 times the rms level.

**Fig. 17.** Moment zero map of the N\(^2\)H\(^+\) emission from B1c with uniform weighting. The new resolution is \(3.09'' \times 2.52''\), almost a factor of 2 improved over the data in Figure 14. The cavity can now be seen as an absence of N\(^2\)H\(^+\) emission offset to the west of the continuum peak, marked by a cross. The triangle marks the position of the source as determined from the SCUBA data; the ring depicts the JCMT beam of \(14''\). Contours are the same as in Figure 10.

We have detected a gradient in \(V_{LSR}\) of N\(^2\)H\(^+\) consistent with rotation; moment maps reveal evidence of a rotating torus offset from the continuum peak position. B1c is similar to the more luminous source L483. Both L483 and B1c show C\(^{18}\)O toward the source peak and an anticorrelation of C\(^{18}\)O with N\(^2\)H\(^+\), indicating that the interior is warm and that CO has been desorbed from grains in that core interiors. In a subsequent paper (Matthews et al. 2006, in preparation), we will model the centrally heated region within the B1c core using new data from the SubMillimeter Array.

Based on the 3.3 mm dust continuum emission, we estimate that the mass of the B1c inner envelope is in the range of \(2.1 - 2.9 M_\odot\). This is consistent with the mass of \(2.4 M_\odot\) derived from the JCMT observations of Kirk, Johnstone & Di Francesco (2004) for a mean dust temperature of 15 K. However, the 3.3 mm measurement is only an estimate of the inner envelope due to the spatial filtering of the BIMA array data.

It is interesting to note that this core exhibits many features of the standard picture for an evolving young stellar object. In continuum dust emission, the core has a dense centrally peaked interior. However, the N\(^2\)H\(^+\) \(J = 1 - 0\) emission appears elongated along an orientation roughly orthogonal to its outflow. The two N\(^2\)H\(^+\) peaks suggest the presence of a rotating torus (with \(r \sim 1000\) AU) with a central cavity carved out by the outflow and heating by the central source. We argue the heating has released \(^{12}\)CO and its isotopes from grains near the central source, destroying N\(^2\)H\(^+\). N\(^2\)H\(^+\) survives in the rest of the inner envelope, as indicated by the torus (or pseudodisk) and the N\(^2\)H\(^+\) emission which brackets the outflow as traced in \(^{12}\)CO \(J = 1 - 0\) and HCO\(^+\) \(J = 1 - 0\). As is the case in L483, the double peaks of N\(^2\)H\(^+\) (torus) do not lie orthogonal to the outflow orientation. In B1c, the offset is \(\sim 65^\circ\).

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