Very Large Array Ammonia Observations of the HH 111/HH 121 Protostellar System: A Detection of a New Source with a Peculiar Chemistry

Marta Sewilo1,6, Jennifer Wiseman1, Remy Indebetouw2,3, Steven B. Charnley1, Johan E. Lindberg1 and Sheng-Li Qin5

1 NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA; marta.m.sewilo@nasa.gov
2 Department of Astronomy, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA
3 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
4 The Center for Astrochemical Studies of the Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse 1, D-85748 Garching, Germany
5 Department of Astronomy, Yunnan University, and Key Laboratory of Astroaparticle Physics of Yunnan Province, Kunming, 650091, China

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Abstract

We present the results of Very Large Array NH3 (J, K) = (1, 1) and (2, 2) observations of the HH 111/HH 121 protostellar system. HH 111, with a spectacular collimated optical jet, is one of the most well-known Herbig–Haro objects. We report the detection of a new source, NH3–S, in the vicinity of HH 111/HH 121 (~0.03 pc from the HH 111 jet source) in two epochs of the ammonia observations. This constitutes the first detection of this source, in a region that has been thoroughly covered previously by both continuum and spectral line interferometric observations. We study the kinematic and physical properties of HH 111 and the newly discovered NH3–S. We also use HCO+ and HCN (J = 4 – 3) data obtained with the James Clerk Maxwell Telescope and archival Atacama Large Millimeter/submillimeter Array 12CO, 13CO, and C18O (J = 2 – 1), N2D+ (J = 3 – 2), and 13CS (J = 5 – 4) data to gain insight into the nature of NH3–S. The chemical structure of NH3–S shows evidence for “selective freeze-out,” an inherent characteristic of dense cold cores. The inner part of NH3–S shows subsonic nonthermal velocity dispersions indicating a “coherent core,” while they increase in the direction of the jets. Archival near- to far-infrared data show no indication of any embedded source in NH3–S. The properties of NH3–S and its location in the infrared dark cloud suggest that it is a starless core located in a turbulent medium, with the turbulence induced by Herbig–Haro jets and associated outflows. More data are needed to fully understand the physical and chemical properties of NH3–S and if/how its evolution is affected by nearby jets.

Key words: astrochemistry – Herbig–Haro objects – methods: data analysis – stars: formation

1. Introduction

The Herbig–Haro object HH 111 is one of the prototypical examples of highly collimated optical jet sources (Reipurth 1989). It is located in the L1617 dark cloud of the Orion B molecular cloud at a distance of 400 pc (e.g., Sandstrom et al. 2007). The infrared source IRAS 05491+0247 (or VLA-1 in Reipurth et al. 1999) is the driving source of the jet. This Class I protostar with an infalling, flattened envelope and circumstellar disk has the luminosity of ~25L⊙ (Reipurth et al. 1992) and is deeply embedded in a 30 M⊙ molecular cloud core (Reipurth & Olberg 1991; Stapelfeldt & Scoville 1993). The total extent of the HH 111 jet complex is 367″ (or ~0.7 pc; Reipurth et al. 1999); it consists of a blueshifted, highly collimated, and bright optical jet; a redshifted faint counterjet; and several bow shocks. The HH 111 jet originates in the high-extinction region and its base is associated with a reflection nebula illuminated by the protostar VLA-1. The proper motions along the jet are large (~300–600 km s⁻¹), and it moves at an inclination angle of 10° to the plane of the sky. The dynamical age of the complex is 800 years (Reipurth et al. 1992). A second pair of bipolar jets (HH 121) was discovered in the near-infrared (Greder & Reipurth 1993; see Figure 1); it intersects HH 111 near the position of the central source at an angle of 61°, suggesting that the driving source of the HH 111 jet may be a binary. Reipurth et al. (1999) argue that the quadrupolar morphology of VLA-1 in the 3.6 cm images suggests that it is a close binary with a projected separation of <0″1 (~40 au at 400 pc).

The HH 111 jet is associated with a large well-collimated molecular outflow (e.g., Reipurth & Olberg 1991; Cernicharo & Reipurth 1996; Nagar et al. 1997). Based on the CO kinematic data, Cernicharo & Reipurth (1996) concluded that the CO flow surrounds the Herbig–Haro jet. A second well-defined bipolar molecular flow in the region coincides with the HH 121 infrared jet.

HH 111 has been a target of multiple interferometric observations (e.g., the Submillimeter Array, Owens Valley Radio Observatory, and Nobeyama Millimeter Array; see Section 3.1), with resolutions ranging from less than one to a few arcsec. The morphology, chemistry, and kinematics of the envelope and the disk of the source exciting the HH 111 jet have been studied in detail.

In this work, we present the results of the Very Large Array (VLA) NH3 (1, 1) and (2, 2) observations of the HH 111/HH 121 protostellar system and its surroundings. Ammonia offers a valuable probe of both gas density and temperature. We discuss the distribution, kinematics, and physical properties of the gas. We report the discovery of an NH3 source in the vicinity of HH 111/HH 121 (~15″ or ~6000 au) and explore its nature using ancillary mid- to far-infrared, and (sub) millimeter continuum and molecular line data. These multi-wavelength observations combined with the ammonia data allow us to determine the chemical structure of the newly discovered NH3 source, its physical parameters (including the temperature, density, and mass), the velocity structure, and nonthermal motions, and to assess the stellar content. The location of the source close to two Herbig–Haro objects...
suggests that the environment may be an important factor in its formation and evolution. Theoretical models show that although outflow-driven turbulence (or “protostellar turbulence”) can suppress/delay global star formation, they can induce star formation on small scales by dynamical compression of pre-existing dense cores (e.g., Nakamura & Li 2007).

The observations, data reduction, and the ancillary data are described in Section 2. In Section 3, we present a detailed analysis of the NH₃ data and discuss the results in the context of the physical and chemical characteristics of the region. A discussion on the nature of the newly discovered NH₃ source is provided in Section 4. The summary and conclusions are given in Section 5.

2. The Data

In this section, we describe the VLA NH₃ (1, 1) and (2, 2) and the James Clerk Maxwell Telescope (JCMT) HCO⁺ and HCN observations and data reduction. We also describe the analysis of the archival Atacama Large Millimeter/submillimeter Array (ALMA) Band 6 data and provide information on the ancillary Spitzer Space Telescope mid-infrared and Herschel Space Observatory far-infrared/submillimeter data.

2.1. VLA

The ammonia data were obtained with the “historical” VLA of the National Radio Astronomy Observatory in June 1999 (AW512) and August 2000 (AW543) in the D configuration. The ammonia (J, K) = (1, 1) and (2, 2) inversion transitions with rest frequencies of 23,694.506 MHz and 23,722.634 MHz, respectively, were observed simultaneously. The instrumental parameters, as well as the flux densities of the flux, bandpass, and phase calibrators, are summarized in Table 1. The data were calibrated using the Astronomical Image Processing System software package.

The calibrated VLA data were further analyzed using the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007). The data were imaged and deconvolved interactively using the CASA task clean. A natural weighting was used and a 20 kλ taper was applied to the UV data. The resulting synthesized beams are listed in Table 1. The data cubes were corrected for the primary beam attenuation using the CASA task impbcor. Both NH₃ (1, 1) and (2, 2) line emission were detected in Epoch 2 and only the (1, 1) line was detected in Epoch 1. Due to some technical difficulties and bad weather conditions during the observations, the overall quality of the Epoch 1 data is significantly lower than that of Epoch 2. As a consequence, only the Epoch 2 data will be used in further analysis. However, within uncertainties, the NH₃ (1, 1) integrated flux density and (2, 2) upper limit from Epoch 1 agree with the detections in Epoch 2. The noise levels in the Epoch 2 NH₃ (1, 1) and (2, 2) data cubes determined from the line-free channels are 7.9 mJy beam⁻¹ and 7.7 mJy beam⁻¹, respectively.

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Table 1

| Parameter | Epoch 1 | Epoch 2 |
|-----------|---------|---------|
| Program ID | AW512 | AW543   |
| Observation dates | 1999 Jun 1–2 | 2000 Aug 24 |
| Total observing time (hr) | ~3.8 | ~2.2 |
| Configuration | D⁺ | D⁺ |
| Number of antennas | 27⁺ | 27⁺ |
| Rest frequency of the NH₃ lines (MHz): | (1, 1) 23,694.506, 23,694.506 | (2, 2) 23,722.634, 23,722.634 |
| Correlator mode | 2AD | 2AD |
| Bandwidth (kHz) | 1550.3 | 1550.31 |
| Number of channels | 127 | 127 |
| Channel separation (kHz) | 12.207 | 12.207 |
| Velocity resolution (km s⁻¹) | 0.154 | 0.154 |
| FWHM of the primary beam (") | 2.1 | 2.1 |
| FWHM of the synthesized beam (" × ′), P.A. (") | 8.38 ± 5.81, 42.3 | 7.86 ± 6.54, −10.0 |
| (2, 2) | 8.02 ± 6.46, −4.6 |
| Flux density calibrator (Jy): | 0542+498 / 3C 147 (IF 1) | 1.73 | 1.81 |
| 0542+498 / 3C 147 (IF 2) | 1.73 | 1.85 |
| Phase calibrator (Jy): | 0532+075 (IF 1) | 1.67 ± 0.06 | 1.05 ± 0.01 |
| 0532+075 (IF 2) | 1.77 ± 0.07 | 1.04 ± 0.01 |
| Bandpass calibrator (Jy): | 0319+415 / 3C 84 (IF 1) | 11.5 ± 0.4 | 11.3 ± 0.2 |
| 0319+415 / 3C 84 (IF 2) | 12.3 ± 0.5 | 11.3 ± 0.2 |

Notes.

⁺ The array was in transition to the A configuration. As a result, the data from four antennas that were already moved had to be discarded.

⁺⁺ The largest angular scale structure that can be imaged in full 12 hr synthesis observations in the D array at 22 GHz is 66″.

2.2. JCMT

HCO⁺ (4–3) and HCN (4–3) emission from the HH 111/HH 121 protostellar system was observed using the Heterodyne Array Receiver Program (HARP) and the Auto-Correlation Spectral Imaging System (ACSIS; Buckle et al. 2009) at the JCMT on Mauna Kea, Hawaii, on 2016 October 16 and 17 (Project ID: M16BP057). The on-source integration time was 53 minutes and 49 minutes for the HCO⁺ and HCN observations, respectively.

HARP has 16 detectors (receivers) arranged in a 4 × 4 configuration with an on-sky projected beam separation of 30″; 14 out of the 16 detectors were functional during the observations. The half-power beam width of each receptor is approximately 14″. The observations at 356.734 GHz (HCO⁺ 4–3) and 354.505 GHz (HCN 4–3) were carried out with the HARP/ACSIS jiggle beam-switching mode using the map-centered HARP4 jiggle pattern. The resulting 2″ × 2″ HCO⁺ and HCN images are centered on (R.A., decl.; J2000) = (5°5′13′′;46″325, +28°48′24″47). At 345 GHz, the main beam efficiency for HARP is 0.64. The weather conditions were dry with 725 GHz ∼ 0.045 for both observing runs. ACSIS was in the single sub-band mode with a bandwidth of 250 MHz separated into 8193 30.5 kHz channels. The resulting velocity resolution is 0.026 km s⁻¹.

The data were reduced using the ORAC Data Reduction pipeline (ORAC-DR) described in Jenness et al. (2015).
Table 2
Summary of the ALMA Archival Molecular Line Data

| Molecule  | Transition | Frequency (GHz) | Δν^1 | Synth. Beam: (θ_{maj}, P.A.) (″ × ″) |
|-----------|------------|----------------|------|-----------------------------------|
| 12CO      | (2−1)      | 220.39686      | 0.2  | 0.84 × 0.67, −79.3               |
| C^{18}O   | (2−1)      | 219.56035      | 0.2  | 0.84 × 0.72, −81.2               |
| N_{2}D^{+}| (3−2)      | 231.32183      | 0.7  | 0.81 × 0.67, −87.4               |
| 13CS      | (5−4)      | 231.22069      | 0.7  | 0.81 × 0.67, −87.4               |

Note.
* The final velocity resolution.

2.3. ALMA

HH 111 was observed with ALMA in Band 6 as part of project 2012.1.00013.S using both the 12 m and 7 m arrays. The J = 2−1 transitions of 12CO, 13CO, and C^{18}O were observed simultaneously with the 230 GHz continuum. The correlator settings for 12CO and C^{18}O used 30.518 kHz channels and a spectral resolution (with online Hanning smoothing) of 0.083 km s\(^{-1}\). HH 111 (corresponding to the ammonia source we refer to as NH₃−Main in this paper) was the target of these observations; however, the images are large enough to cover the newly discovered ammonia source, which we dubbed NH₃−S.

The project was executed three times in May 2014 using the 12 m array with baselines from 20 to 558 m, for a total time on source of 144 minutes. Absolute flux calibration of the three executions was performed using Ganymede, J0510+180 (1.27 Jy at 220 GHz), and Callisto. Bandpass and phase calibration were performed using J0607−0834 (1.5 Jy) and J0532+0732 (630 mJy), respectively. For the 7 m array, data from 18 executions between 2013 December 15 and 2014 December 14 were of good quality, incorporating baselines from 9 to 49 m and a total of 414 minutes on source. Absolute flux calibration used Ganymede, Callisto, Pallas, J0510+180, and J0423−013 (one execution only; 840 mJy at 220 GHz). J0750+1231 (1.1 Jy at 220 GHz) was used for bandpass calibration, and phase calibration used either J0532+0732 (500−1400 mJy at 220 GHz during the course of these observations) or J0607−0834 (1.3 Jy at 220 GHz). The complete list of ALMA Science Data Model (ASDM) UIDs used is provided in Appendix A.

The calibration in the archive was performed with several different CASA versions as the data were taken, so to ensure correct data weighting, we retrieved the raw visibility data and calibrated them using the ALMA calibration pipeline included in the CASA 4.5.3 package.

Continuum was subtracted in the uv domain from each line spectral window, and the 7 m and 12 m data were simultaneously imaged and deconvolved interactively. Synthesized beams for 12CO and C^{18}O are 0.384 × 0.367 and 0.384 × 0.372, respectively. The noise levels in the images away from line center are 4.5 and 3.5 mJy beam\(^{-1}\), respectively, but 12CO shows evidence of significant resolved-out large-scale flux near the line center and an effective image fidelity floor of ~15 mJy beam\(^{-1}\) at those velocities. The velocity resolution of the 12CO and C^{18}O data cubes is 0.2 km s\(^{-1}\).

The ALMA observations also covered other spectral lines with lower spectral resolution (~0.7 km s\(^{-1}\)). These include the N₂D\(^{+}\) (3−2) and 13CS (5−4) molecular lines. The data cubes were corrected for the primary beam attenuation using the CASA task impbcor. The noise levels in the final N₂D\(^{+}\) and 13CS images are 1.8 and 1.1 mJy beam\(^{-1}\), respectively.

The ALMA C^{18}O data for HH 111 were presented in Lee et al. (2016). Here we use qualitatively the C^{18}O data, as well as previously unpublished 12CO, 13CO, and 13CS data, to investigate the nature of the newly discovered source NH₃−S (see Section 4). We discuss the ALMA N₂D\(^{+}\) observations in more detail (see Section 3.3).

2.4. Ancillary Archival Data: Spitzer and Herschel

We use archival data from the Spitzer Space Telescope and the Herschel Space Observatory.

The Spitzer data were downloaded from the Spitzer Heritage Archive (SHA) and include two epochs of observations. The first data set was obtained in 2005 (GO 3315, PI: A. Noriega-Crespo) and includes the observations with both the “Infrared Array Camera” (IRAC; Fazio et al. 2004; 3.6, 4.5, 5.8, and 8.0 μm) and “Multiband Imaging Photometer for Spitzer” (MIPS; Rieke et al. 2004; 24, 70, and 160 μm). The spatial resolution of the IRAC observations is ~2′, and the resolutions of the MIPS 24, 70, and 160 μm data are 6′, 18′, and 40′, respectively. The 2012 data (GO 80109, PI: J. Kirkpatrick) were taken during the warm Spitzer mission and thus only 3.6 and 4.5 μm data are available. The 2005 IRAC post-baseline calibrated data (Post-BCD) have been presented in Noriega-Crespo et al. (2011). Here we use the Spitzer Enhanced Imaging Products and “Super Mosaics” provided in the SHA for the cryogenic mission. We use the Post-BCD Level 2 mosaics from the 2012 observations.

The Herschel Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) 70 and 160 μm and the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) 250, 350, and 500 μm mosaics were downloaded from the Herschel Science Archive (Proposal ID: OT1_tbell_1). The data were obtained in 2003 and are Level 3 (SPIRE) and Level 2 (PACS) processed (the pipeline used the Standard Product Generation software v13.0.0); no further data processing was done for our analysis. The nominal spatial resolution of the Herschel data ranges from ~5′ at 70 μm to ~35′ at 500 μm.

3. Observational Results

3.1. NH₃ Emission

The NH₃ (1, 1) and (2, 2) images shown in Figure 2 reveal two sources. One of the ammonia sources coincides with HH 111, tracing an envelope of the source associated with the jet. The second source located ~15″ (~0.029 pc or 6000 au at 400 pc) to the southeast is a new detection and is even more prominent; we dubbed this source NH₃−S to distinguish it from the source associated with HH 111 that we refer to as NH₃−Main throughout this paper. The NH₃ emission in NH₃−Main does not peak directly on the protostar, but is offset by ~5″ (~0.01 pc or 2000 au) toward the southwest. This offset may indicate the drop in NH₃ abundance at the location of the protostar caused by the depletion or destruction of the molecules (e.g., Belloche et al. 2002; Tobin et al. 2011). Both NH₃−S and NH₃−Main were also detected in the Epoch 1 data (see Figure 3).

The HH 111/HH 121 protostellar system and its surroundings have been thoroughly covered by observations over the broad wavelength range (from the optical to centimeter
wavelengths), yet NH$_3$–S remained undetected until our NH$_3$ observations. NH$_3$–S has not been reported as detected in any of the single-dish and interferometric molecular line observations (e.g., CO, $^{13}$CO, C$^{18}$O, SO, CS; see Section 1) or the centimeter- and millimeter-wave continuum observations with the VLA (e.g., Reipurth et al. 1999 at 3.6 cm; a resolution of $\sim$0"4) and SMA (e.g., Lee 2010 at 1.3 mm; $\sim$1"). The molecular lines observed interferometrically include CO J = 1–0 (Le Floc’h et al. 2007; $\sim$3"), CO 2–1 (Lee 2011; $\sim$0"6), $^{13}$CO 1–0 (Stapelfeldt & Scoville 1993; $\sim$7") $^{13}$CO 2–1 (Lee et al. 2009; $\sim$3") C$^{18}$O 2–1 (Lee et al. 2009; Lee 2010, 2011; $\sim$0"3–3") and SO 5$_{0}$–4$_{5}$ (Lee et al. 2009; Lee 2010, 2011; $\sim$0"3–3") We also checked the 2MASS (JHK), Spitzer (3.6–160 $\mu$m), WISE (3.5–22 $\mu$m), and Herschel (70–500 $\mu$m) archival data and found that no source was detected at the position of NH$_3$–S with these facilities. Example images of the region showing a nondetection of NH$_3$–S are shown in Figure 4.

Figure 1. Three-color composite image of HH 111/HH 121, combining the Spitzer IRAC 8 $\mu$m (red), 4.5 $\mu$m (green), and 3.6 $\mu$m (blue) images. The HH 111 (∼E–W) and HH 121 (∼N–S) jets are clearly seen in the 4.5 $\mu$m emission. Two ammonia sources are indicated with arrows and labeled. The contours represent the NH$_3$ (1, 1) emission; the contour levels are (20, 40, 60, 75, 95)% of the NH$_3$ (1, 1) integrated intensity peak of 86.9 mJy beam$^{-1}$ km s$^{-1}$ (see Figure 2). The Spitzer/IRAC resolution is $\sim$2". The VLA synthesized beam is $\sim$7"9 $\times$ 6"5. The linear scale shown in the lower right corresponds to a distance of 400 pc. North is up and east to the left.

Figure 2. Epoch 2 integrated intensity images of the main NH$_3$ (1, 1) and (2, 2) line components (left and right panels, respectively). Two radio continuum sources associated with HH 111 are indicated with filled circles and labeled (see also Figure 4). The NH$_3$ (1, 1) contour levels are (20, 40, 60, 75, 95)% of the integrated intensity peak of 86.9 mJy beam$^{-1}$ km s$^{-1}$. The NH$_3$ (2, 2) contour levels are (60, 80, 95)% of the integrated intensity peak of 24.7 mJy beam$^{-1}$ km s$^{-1}$. The VLA synthesized beam is shown in the lower-right corner in each image.

3.1.1. Ammonia Line Profile Fitting

Ammonia constitutes an ideal probe of the physical conditions in the ambient molecular material (e.g., Ho et al. 1979;
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NH$_3$ (1, 1) Integrated intensity image for the Epoch 1 observations (AWS12; see Table 1). Both sources, NH$_3$–Main and NH$_3$–S, are detected. The contour levels are (25, 50, 75, 95)% of the intensity peak of 0.07 Jy beam$^{-1}$ km s$^{-1}$.

The size of the synthesized beam shown in the lower-right corner of the image is 8$''$38 $\times$ 5$''$81.

Figure 3.

Ho & Townes 1983; Harju et al. 1993; Busquet et al. 2009). Ammonia has a distinctive spectrum with a main line and a pair of satellite lines on each of its sides; in total, these lines are composed of 18 distinct hyperfine components. The optical depth of the transition can be calculated directly from the brightness temperature ratio of the satellite to the main lines of the NH$_3$ spectrum, facilitating the calculation of the excitation temperature. When two or more NH$_3$ transitions are observed, it is possible to calculate a rotational temperature describing the relative populations of the different energy states and the column densities. The rotational temperatures can be converted to kinetic temperatures based on models of the collisional excitation of NH$_3$ (e.g., Danby et al. 1988; Tafalla et al. 2004).

Our VLA ammonia observations cover the main line and the inner satellite components of the NH$_3$ spectrum. We detected both the main line and satellite components for the (1, 1) transition, and only the main line for the (2, 2) transition (see Figure 5). We use the NH$_3$ (1, 1) and (2, 2) lines to determine the physical properties of NH$_3$–Main and NH$_3$–S.

Here we fit simultaneously all observed hyperfine components of the NH$_3$ (1, 1) and (2, 2) lines using a forward model presented by Friesen et al. (2017). This method describes the emission at every position with a centroid velocity ($V_{\text{LSR}}$), velocity dispersion ($\sigma_v$), kinetic temperature ($T_{\text{kin}}$), excitation temperature ($T_{\text{ex}}$), and the total NH$_3$ column density ($N$(NH$_3$)). We adopt the local thermodynamic equilibrium (LTE) value of 1 for the ortho- to para-NH$_3$ ratio. The kinetic temperature is derived from the rotational temperature assuming that only the (1, 1) and (2, 2) levels are significantly populated. The model is implemented in the Python analysis toolkit pyspeckit as “cold-ammonia” (Ginsburg & Mirocha 2011). We fit the NH$_3$ line profiles on a pixel-by-pixel basis to construct the maps of the physical parameters. The fitting was done for pixels with a signal-to-noise ratio for the NH$_3$ (1, 1) line larger than 5.

Figures 6 and 7 show the maps of, respectively, the NH$_3$ (1, 1) line velocity ($V_{\text{LSR}}$) and the FWHM ($\Delta V = \sqrt{8 \ln 2} \sigma_v$, where $\sigma_v$ is the velocity dispersion, directly related to gas temperature; see Section 3.1.4). Figure 8 shows the maps of $T_{\text{kin}}$, $N$(NH$_3$), and $T_{\text{ex}}$. The maps of the physical parameters estimated based on both the NH$_3$ (1, 1) and (2, 2) lines, $T_{\text{kin}}$ and $N$(NH$_3$), cover the relatively small areas where the NH$_3$ (2, 2) line was detected (see Figure 8). The maps of $T_{\text{ex}}$ in Figure 8 are shown for the same area as for $T_{\text{kin}}$ and $N$(NH$_3$).

3.1.2. Velocity Structure

The $V_{\text{LSR}}$ map shows that NH$_3$–S and NH$_3$–Main appear to be kinematically distinct sources with a velocity difference of about 1 km s$^{-1}$ (Figure 6). The mean $V_{\text{LSR}}$ of NH$_3$–S and NH$_3$–Main is 9.2 km s$^{-1}$ and 8.6 km s$^{-1}$, respectively (see Table 3). A clear velocity gradient roughly from the southeast to the northwest is detected in NH$_3$–S. A velocity gradient of 7.3 km s$^{-1}$ pc$^{-1}$ was measured along the line with the position angle of 104$^\circ$6 and length of 0.027 pc intersecting the peak of the NH$_3$ (1, 1) emission.

Although velocity gradients can be identified in the $V_{\text{LSR}}$ map for NH$_3$–Main, they are less organized than in NH$_3$–S. In general, the western part of the source has lower velocities than the eastern part. There is no evidence for a velocity gradient in the direction perpendicular to the HH 111 jet that would trace the rotation of the protostellar envelope of VLA-1; such a gradient has been detected with C$^{18}$O (see Lee 2010 and Figure 11). The kinematics of this region are very complex due to the presence of two outflows, as well as the infall and rotation in the protostellar envelope.

A sharp transition in velocity between NH$_3$–Main and NH$_3$–S (Figure 6) and increased line widths at this location (Figure 7) are likely artifacts, the result of the hyperfine fitting of the line profiles formed by the significant blending of two velocity components; the individual lines are not clearly distinguishable.

Tobin et al. (2011) found two distinct velocity components in the $N_2$H$^+$ images of four protostars: L673, HH 211, HH 108, and RNO 43. They also observed regions with artificially broadened lines where these velocity components overlap. The second velocity component in L673, HH 211, HH 108, and RNO 43 is located at a distance of ~0.05 pc from the protostar, comparable to the distance between VLA-1 and NH$_3$–S in HH 111/HH 121 (~0.04 pc). Tobin et al. (2011) suggest that the reason for the two velocity components in a single region could be related to the initial conditions in the clouds. It is in agreement with the theory of turbulent star formation in which cloud cores are initially created and confined by the ram pressure from convergent large-scale flows (e.g., Padoan et al. 2001; MacLow 2004; Klessen et al. 2005; Pineda et al. 2015). These cores are transient, dynamically evolving density fluctuations that will either collapse and transform into stars (if they accumulate enough mass), re-expand and dissolve into the surrounding environment, or be destroyed by shock fronts (Klessen et al. 2005). The velocity difference of $\lesssim$1 km s$^{-1}$ between NH$_3$–Main and NH$_3$–S can be explained by the turbulent star formation model.

3.1.3. Physical Parameters

The physical parameters averaged over the areas shown in Figure 8 together with the standard deviations are listed in Table 3 for NH$_3$–Main and NH$_3$–S.

For NH$_3$–S, the physical parameters are determined for the central part of the core, roughly corresponding to the area of the synthesized beam (see Figure 8). The distribution of both $T_{\text{ex}}$ and $N$(NH$_3$) is centrally peaked and well-correlated with the...
peak of the NH$_3$ emission. The distribution of $T_{\text{kin}}$, however, shows a gradient across the core from $\sim$11.4 K in the south to $\sim$13.4 K in the northeast.

Due to the much fainter NH$_3$ (2, 2) line emission from NH$_3$–Main, it was possible to determine $T_{\text{kin}}$ and $N$(NH$_3$) for only a small fraction of the source area, corresponding to $\sim$20% of the beam. The $T_{\text{kin}}$, $N$(NH$_3$), and $T_{\text{ex}}$ maps show the gradients of these quantities over this small area (see Figure 8), with the maximum $T_{\text{kin}}$ and $T_{\text{ex}}$ associated with the peak of the NH$_3$ (1, 1) emission. As a consequence of the small source...
is the mass of the hydrogen

\(m\) spatially and kinematically distinct sources. The velocities were determined for pixels with signal-to-noise ratio larger than 5 (see Section 3.1.3). The middle and right panels show the velocity maps of the individual sources NH\(_3\)-Main and NH\(_3\)-S, respectively; these images provide a more detailed look at the velocity distribution for each source. The middle panel shows the regions with velocities lower than 8.9 km s\(^{-1}\), while the right panel shows those with velocities larger than or equal to 8.9 km s\(^{-1}\). The NH\(_3\) (1, 1) contours are as in Figure 2. The VLA synthesized beam is shown in the lower-right corner in each image.

To estimate the sizes of both NH\(_3\)-S and NH\(_3\)-Main, we drew a polygon around the contour at the half-maximum level for each source and derived the area within the contour (A), which we used to estimate the “effective” angular diameter of the source (or FWHM\(_{\text{eff}}\)) using the equation FWHM\(_{\text{eff}} = 2\sqrt{\lambda/\pi}\) (see, e.g., Kauffmann et al. 2013; Sánchez-Monge et al. 2013). Assuming the sources are Gaussian, we calculated the deconvolved sizes \(\theta\) from \(\theta = \sqrt{\text{FWHM}_{\text{HPBW}}^2/\text{HPBW}^2}\), where the half-power beam width (HPBW) is the geometric mean of the minor and major axes of the synthesized beam (see Table 1). The estimated sizes of NH\(_3\)-S and NH\(_3\)-Main are 9\(\"\)5 and 14\(\"\)4 or 0.018 pc and 0.028 pc, respectively.

The molecular mass of the core can be calculated from the equation

\[ M_{\text{NH}_3} = \frac{N(\text{NH}_3)}{X} \mu m_H A, \]

(1)

where \(N(\text{NH}_3)\) is the total ammonia column density, \(X\) is the [\(\text{NH}_3\)/H\(_2\)] abundance ratio, \(\mu\) is the mean molecular weight per hydrogen molecule (\(\mu = 2.8\)), \(m_H\) is the mass of the hydrogen atom, and \(A\) is the area of the source. We adopt \(X = 10^{-8}\), we note, however, that the observed fractional abundance values range from a few times \(10^{-5}\) to a few times \(10^{-3}\) for dense, cold regions (e.g., Harju et al. 1993; Larson et al. 2003; Foster et al. 2009; Friesen et al. 2009). Using the \textsf{imfit} results to determine the source area, we estimate the molecular mass of the NH\(_3\)-S core to be 0.25 \(M_\odot\). If we use the areas within the contours at the half-maximum level (see above), we obtain NH\(_3\)-S and NH\(_3\)-Main masses of 0.33 \(M_\odot\) and 0.37 \(M_\odot\), respectively.

Masses can also be estimated based on the ALMA 1.3 mm continuum data. In high-density regions, it is expected that \(T_{\text{kin}}\) is approximately equal to the dust temperature \((T_d)\), due to the good coupling between the gas and dust. Using the dust temperature, we can estimate the upper limit for the cloud mass for NH\(_3\)-S from the ALMA 1.3 mm continuum data. Assuming optically thin dust continuum emission, the dust mass can be estimated from the equation

\[ M_{\text{dust}} = \frac{S_d D^2}{\kappa_v B_{\nu}(T_d)}, \]

(2)

\(S_d\) is the observed flux density, \(D\) is the distance to the source, \(\kappa_v\) is the absorption coefficient at the wavelength of observation, and \(B_{\nu}(T_d)\) is the Planck function at the dust temperature.

\(\frac{\Delta v}{\text{FWHM}}\): an FWHM corrected for instrumental broadening) map of HH 111/HH 121. The line widths were determined for pixels with signal-to-noise ratio larger than 5 (see Section 3.1.3). The red arrows show the approximate directions of the HH 111 and HH 121 jets. The NH\(_3\) (1, 1) contours are as in Figure 2. The VLA synthesized beam is shown in the lower-right corner.

\(\Delta v\) for NH\(_3\)-Main cannot be determined.

For both NH\(_3\)-Main and NH\(_3\)-S, \(T_{\text{ex}}\) is lower than \(T_{\text{kin}}\), indicating that the ammonia inversion lines are mostly subthermally excited; the density is too low for the local populations to go to LTE (e.g., Evans 1989; Shirley 2015). This is consistent with the results found by Friesen et al. (2017).

The CASA task \textsf{imfit} was used to fit a two-dimensional Gaussian component to the NH\(_3\) (1, 1) integrated intensity emission from NH\(_3\)-S to estimate the source’s angular diameter. The FWHMs of the deconvolved major and minor axes are 11\(\"\)6 and 5\(\"\)9 (0.023 \times 0.011 pc), respectively, with an estimated uncertainty of \(\sim 20\%\). We did not obtain a satisfactory fit for NH\(_3\)-Main, possibly due to its more complex geometry.
where $S_\nu$ is the integrated flux density, $D$ is the distance to the source, $B_\nu(T_\text{dust})$ is the Planck function, and $\kappa_\nu$ is the dust opacity per unit mass at frequency $\nu$ (e.g., Hildebrand 1983; Shirley et al. 2000). The clump mass ($M_{\text{clump}}$) can be derived by multiplying the dust mass by the gas-to-dust ratio $R_{gd}$: $M_{\text{clump}} = M_{\text{dust}} R_{gd}$. We used the Ossenkopf & Henning (1994) MRN distribution (Mathis et al. 1977) with thin ice mantles after $10^5$ years of coagulation at a gas density of $10^6$ cm$^{-3}$ model for dust opacity. For 1.3 mm, $\kappa_{1.3 \text{ mm}}$ equals 0.899 cm$^2$ g$^{-1}$ (or 0.009 cm$^2$ g$^{-1}$ for $R_{gd} = 100$) for prestellar cores. Assuming an $R_{gd}$ of 100, the clump mass can be expressed by the formula

$$M_{\text{clump}}(M_\odot) = 0.12 \left(\frac{\kappa_\nu}{0.01 \text{ cm}^2 \text{ g}^{-1}}\right)^{-1} \left(\frac{S_\nu}{\text{Jy}}\right) \left(\frac{D}{100 \text{ pc}}\right)^2 \left(\frac{\lambda}{\text{mm}}\right)^3. $$(3)

Since NH$_3$–S has not been detected at 1.3 mm with ALMA, we adopt $3\times$ the image rms for $S_{1.3 \text{ mm}}$ to calculate the mass upper limit. Adopting the distance of 400 pc, the temperature of 12.1 K, and the flux density of 1.8 mJy beam$^{-1}$, the upper limit for the NH$_3$–S clump mass is 0.013 $M_\odot$ per beam, which corresponds to $\sim$1.7 $M_\odot$ if we adopt a source size determined from the ammonia data ($\sim$127.5 ALMA beams at 1.3 mm). As the observations show, in general there is a good correspondence between the distribution of the ammonia and dust emission (see, e.g., Friesen et al. 2009). For prestellar dense clumps and cores, $\kappa_{1.3 \text{ mm}} = 0.5$ cm$^2$ g$^{-1}$ (or 0.005 cm$^2$ g$^{-1}$ if $R_{gd}$ is taken into account) is assumed in the literature (e.g., Preibisch et al. 1993; Andre et al. 1996; Motte et al. 1998). If we adopt this value of $\kappa_{1.3 \text{ mm}}$, the estimate of the mass upper limit increases to 0.023 $M_\odot$ per beam, or $\sim$2.9 $M_\odot$.

The value of $\kappa_\nu$ is uncertain as it depends sensitively on the properties of the dust grains (see, e.g., Henning et al. 1995), e.g., the size, shape, chemical composition, the physical structure of the grains, as well as the dust temperature. Ossenkopf & Henning (1994) argue that $\kappa_\nu$ can deviate from their tabulated values by a factor of $\leq 2$ in environments with different physical conditions. Taking into account the uncertainties in the distance, dust temperature, flux density, as well as the assumed gas-to-dust ratio, we estimate that there is a factor of 3–4 uncertainty in the gas mass estimate.

### Table 3

| Source       | R.A. (J2000) (°m s') | Decl. (J2000) (°m s') | $V_{\text{LSR}}$ (km s$^{-1}$) | Size (pc) | $T_{\text{kin}}$(K) | $T_{\text{ex}}$(K) | $N$(NH$_3$) ($10^4$ cm$^{-2}$) | $M_{\text{core}}^a$ ($M_\odot$) |
|--------------|----------------------|-----------------------|---------------------|----------|-------------------|-------------------|-------------------|--------------------------|
| NH$_3$–Main  | 5:51:46.045          | +2:48:25.72           | 8.6 (0.1)           | 0.028    | 11.2 (0.6)        | 8.3 (0.2)         | 2.7 (0.1)         | 0.37                     |
| NH$_3$–S     | 5:51:46.579          | +2:48:11.23           | 9.2 (0.1)           | 0.018    | 12.1 (0.5)        | 7.8 (0.3)         | 5.5 (0.4)         | 0.33                     |

**Note.**

*Masses of the ammonia cores estimated using Equation (1), with $A$ being equal to the areas within the NH$_3$ (1, 1) contour at the half-maximum level for a corresponding source. The linear sizes listed in the “Size” column were estimated from “A” (see the text for details).*
weight of the \( \text{NH}_3 \) molecule in atomic units (\( \mu_{\text{NH}} = 17.03 \)), and \( n_1 \) is the mass of the hydrogen atom. The FWHM line width can be derived by multiplying the velocity dispersion by \( 8 \ln 2 \). The thermal velocity dispersion is \( \sim 0.08 \text{ km s}^{-1} \) and \( \sim 0.07 \text{ km s}^{-1} \) for \( \text{NH}_3 \)–S and \( \text{NH}_3 \)–Main, assuming \( T_{\text{kin}} = 12.1 \text{ K} \) and 11.2 K, respectively. The nonthermal velocity dispersion \( (\sigma_{\text{nth}}) \) can be derived using the equation \( \sigma_{\text{nth}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{th}}^2} \), where \( \sigma_{\text{obs}} \) and \( \sigma_{\text{th}} \) are the observed (corrected for instrumental broadening) and thermal velocity dispersions, respectively. The mean values of \( \sigma_{\text{nth}} \) are 0.16 km s\(^{-1}\) and 0.14 km s\(^{-1}\) for \( \text{NH}_3 \)–S and \( \text{NH}_3 \)–Main, respectively. The respective \( \sigma_{\text{nth}} \) standard deviations are 0.06 km s\(^{-1}\) and 0.07 km s\(^{-1}\).

We compare \( \sigma_{\text{nth}} \) to the thermal sound speed, \( c_s = \sqrt{k_B \ T_{\text{kin}} / (\mu m_1)} \), where \( \mu \) is the molecular weight of a mean particle, \( \mu = 2.33 \). Figure 9 shows maps of \( \sigma_{\text{nth}} / c_s \) for \( \text{NH}_3 \)–S and \( \text{NH}_3 \)–Main. The figure shows that for \( \text{NH}_3 \)–S, nonthermal line widths are smaller than or equal to the thermal line width over most of the core (the core is “quiescent”), except for its northern rim where the core starts having “transonic” nonthermal line-of-sight velocity dispersions (\( \sigma_{\text{nth}} / c_s \approx 2 \); e.g., Klessen et al. 2005). In \( \text{NH}_3 \)–Main, the turbulent velocity...
dispersion increases from the subsonic values on the eastern and western sides of the source to the transonic values in the central strip, and is supersonic in a small area in the north in the vicinity of sources VLA-1 and VLA-2.

The largest turbulent velocity dispersions in NH$_3$–Main and NH$_3$–S occur in regions where the impact of the Herbig–Haro jets and molecular outflows on the environment is expected to be large. This is illustrated in Figure 10, where we compare the distribution of $\sigma_{\text{obs}}/c$ to the $^{12}$CO emission in two representative velocity ranges that trace the outflows associated with both HH 111 and HH 121 jets. In NH$_3$–Main, the region of enhanced turbulent velocity dispersion coincides with the base of the HH 111 jet. The increased line widths in the inner envelope have been observed toward other young objects, including HH 211, L 1157, and L 1451–mm (Tanner & Arce 2011; Tobin et al. 2011; Pineda et al. 2011).

The distribution of the $^{12}$CO emission suggests the possibility that VLA-2 is the source of the HH 121 jet; this conclusion, however, needs to be supported by a detailed analysis of the $^{12}$CO data, which is out of the scope of this paper. NH$_3$–S is located between the HH 111 jet in the north and the HH 121 jet in the northwest and west; the location of the region of enhanced turbulent velocity dispersions along the northern rim of the source and on the northeast and northwest indicates that they may be the result of the turbulence induced by the jets. This scenario will be discussed in more detail in Section 4.

3.2. Carbon-bearing Molecules

We investigate the distribution of the C$^{18}$O (2–1), $^{13}$CO (2–1), and $^{13}$CS (5–4) emission detected by ALMA to gain some insight into the nature of NH$_3$–S. Figures 11–13 show the integrated intensity images and the velocity distributions for C$^{18}$O, $^{13}$CO, and $^{13}$CS, respectively. The $^{12}$CO (2–1) integrated intensity contours are shown in Figure 10. The ALMA C$^{18}$O line and 1.3 mm continuum data for HH 111 is presented in Lee et al. (2016), who studied the envelope and disk of source VLA-1 in great detail.

The carbon-bearing molecular emission traces the envelope and disk of the central source VLA-1 (C$^{18}$O and $^{13}$CS) and the molecular outflow (mainly $^{13}$CO and $^{12}$CO) in the Class I protostellar system HH 111, as well as the molecular outflow associated with the HH 121 jet. This region is associated mainly with the ammonia source NH$_3$–Main. What is striking in Figures 10–12 is the lack of C$^{18}$O, $^{12}$CO, and $^{13}$CO emission in the center of NH$_3$–S. However, the $^{13}$CO and C$^{18}$O emission wraps around the source roughly from east to west along its northern rim. No $^{13}$CS was detected toward NH$_3$–S; the $^{13}$CS emission is confined to the envelope of VLA-1.

The morphology of the $^{13}$CO and C$^{18}$O emission can be inspected in more detail in Figures 21–23 in Appendix B. Figure 21 shows the C$^{18}$O channel maps for the velocity range 4.4–13.8 km s$^{-1}$. Figures 22 and 23 show the three-color mosaics combining the C$^{18}$O and $^{13}$CO channel maps, respectively, with the Spitzer 4.5 μm image and the VLA NH$_3$ (1, 1) channel maps; the C$^{18}$O/$^{13}$CO and NH$_3$ velocity range corresponds to the velocities of the NH$_3$ (1, 1) main line emission toward NH$_3$–S (8.8–9.8 km s$^{-1}$). Several jet knots detected with Spitzer at 4.5 μm allow us to relate the molecular line emission to the HH 111 and HH 121 jets. The $^{18}$CO and $^{13}$CO emission is filamentary south of VLA-1 toward and around NH$_3$–S.

3.3. N$_2$D$^+$

The ALMA N$_2$D$^+$ (3–2) image shown in Figure 14 reveals two N$_2$D$^+$ condensations in the HH 111/HH 121 protostellar system. One of the condensations is associated with NH$_3$–S with the peak N$_2$D$^+$ emission coinciding with the peak of the NH$_3$ emission. The second N$_2$D$^+$ condensation is located in
NH$_3$--Main; it is offset to the southwest from the location of the protostar VLA-1 and to the west from the peak of the NH$_3$ emission. The two N$_2$D$^+$ condensations show a velocity difference of $\sim 0.7$ km s$^{-1}$ (see Figure 14), consistent with the NH$_3$ results. The N$_2$D$^+$ emission appears clumpy; more extended emission has possibly been filtered out by the interferometer.

As will be discussed in Section 4, observable abundances of N$_2$D$^+$ can only be achieved in the coldest and densest molecular cores where CO, the main destroyer of N$_2$D$^+$, is frozen-out onto dust grains (e.g., Caselli et al. 2002b; Flower et al. 2006). N-bearing molecules such as N$_2$D$^+$ and NH$_3$ are used to study the cold material because they do not freeze-out onto dust grains until a density of $\sim 10^6$ cm$^{-3}$ is reached.

Figure 12. ALMA $^{13}$CO integrated intensity (moment 0; left) and LSR velocity (moment 1; right) maps. The $^{13}$CO emission in the velocity range 7.0--11.0 km s$^{-1}$ was used for the moment 0 and moment 1 calculations. Only pixels with a signal-to-noise ratio larger than 10 were included in the moment 1 calculations. The white contours represent the NH$_3$ (1, 1) emission; the contour levels are as in Figure 2. No $^{13}$CO emission was detected toward the center of NH$_3$--S. In both images, the ALMA beam is shown in the lower-left corner.

Figure 13. ALMA $^{12}$CS integrated intensity (moment 0; left) and LSR velocity (moment 1; right) maps. The velocity of the $^{12}$CS emission ranges from 5.5 to 11.1 km s$^{-1}$, this velocity range was used for the moment 0 and moment 1 calculations. Only pixels with a signal-to-noise ratio larger than 5 were included in the moment 1 calculations. The white contours represent the NH$_3$ (1, 1) emission; the contour levels are as in Figure 2. The triangles indicate the positions of the VLA-1 and VLA-2 sources (see also Figures 11 and 12). The $^{12}$CS emission is confined to the envelope of VLA-1; no $^{13}$CS was detected toward NH$_3$--S. The ALMA beam is shown in the lower-left corner.
A nondetection of the CO emission toward the inner part of NH₃–S shows that CO is indeed frozen-out where N₂D⁺ is detected. Also, no CO emission has been detected toward the center of the N₂D⁺ condensation in NH₃–Main in the velocity range corresponding to that of the N₂D⁺ emission (see Figures 11 and 12).

The eastern edge of the N₂D⁺ condensation (as defined by the contour at the level of 20% of the peak) in NH₃–Main and the maximum N₂D⁺ emission pixel are at a distance of ~2"7 (~0.005 pc or ~1100 au) and ~10"8 (~0.02 pc or ~4300 au), respectively, from the protostar VLA-1. These offsets can be explained by the destruction of N₂D⁺ molecules in regions of bright CO emission associated with the protostar.

The NH₃ emission peak coincides with the eastern edge of the N₂D⁺ condensation, but is offset by ~7" (~0.014 pc or ~2800 au) from the maximum N₂D⁺ emission pixel. The N₂D⁺ emission is distributed along the jet rather than in the direction perpendicular to it.

The relative offset between the distribution of the N₂D⁺ and N₂H⁺ emission was detected in eight Class 0/I protostellar envelopes by Tobin et al. (2013). The observations show that N₂H⁺ and NH₃ appear to trace the same kinematics and physical conditions (e.g., Tobin et al. 2011), thus we can expect the offset between the peak NH₃ and N₂D⁺ emission. The distribution of the N₂D⁺ emission with respect to the N₂H⁺ emission for several sources in the Tobin et al. (2013) sample has a similar morphology to that between N₂D⁺ and NH₃ in HH 111/HH 121; for example, L483 and L1165 have N₂D⁺ emission with the peak in the direction of the outflow with N₂H⁺ and N₂D⁺ offsets of ~3200 au and ~2400 au, respectively. Tobin et al. (2013) argue that the abundance peak offsets between N₂H⁺ and N₂D⁺ can be explained by the

---

**Figure 14.** N₂D⁺ (3–2) integrated intensity (moment 0; left) and LSR velocity (moment 1; right) maps. The moment maps were made using the data cube corrected for the primary beam; only pixels with signal-to-noise ratio larger than 4 were included in the moment 1 calculations. The black contours in the left panel correspond to the N₂D⁺ integrated intensity with contour levels of (5, 10, 15) × 2.2 mJy beam⁻¹, the image rms noise. The white contours show the distribution of the NH₃ (1, 1) emission observed with the VLA; the contour levels are as in Figure 2. The size of the ALMA synthesized beam shown in the lower-left/lower-right (left/right) panel corner is 0"81 × 0"67, PA = -87°.

**Figure 15.** N₂D⁺ (3–2) line profiles for the N₂D⁺ clumps associated with NH₃–Main (left) and NH₃–S (right) averaged over the area enclosed by the 20% of the peak contour for a corresponding source. The results of the Gaussian profile fitting are presented in Table 4.
increased CO evaporation temperature due to ice mixtures and/or a gradient of the ortho/para-H$_2$ ratio in the inner envelope.

No velocity gradients are detected in N$_2$D$^+$ in HH 111/HH 121. The N$_2$D$^+$ line profiles for both N$_2$D$^+$ concentrations are presented in Figure 15. For each clump, the line profile was extracted as a mean over an elliptical region enclosing the contour with the value corresponding to 20% of the N$_2$D$^+$ emission peak. No hyperfine components were resolved. The lines are broadened by the hyperfine component blending, nonthermal motions, and a relatively low velocity resolution. We thus fitted the N$_2$D$^+$ lines with single-Gaussian profiles; the results are listed in Table 4. The N$_2$D$^+$ line parameters for both cores are very similar, but higher velocity resolution observations are needed to estimate their physical parameters using the hyperfine emission line structure fitting.

4. Discussion

The properties of NH$_3$–S indicate that it is a starless core located in a turbulent medium with turbulence induced by the Herbig–Haro jets and associated outflows. Dense cores are density enhancements of the cloud material with masses of 0.5–5 $M_{\odot}$, sizes of 0.03–0.2 pc, mean densities of $10^4$–$10^5$ cm$^{-3}$, velocity extents of 0.1–0.3 km s$^{-1}$, and gas temperatures of 8–12 K (see the review by Bergin & Tafalla 2007). The Spitzer 8.0 μm image shows that NH$_3$–S is located in the dark cloud and there is no indication of the presence of the central object in the available observations ranging from near-IR to millimeter wavelengths (see Section 3.1). The chemical structure of the NH$_3$–S core show evidence for “selective” freeze-out, an inherent property of dense cold cores.

NH$_3$–S has characteristics of a “coherent core” (e.g., Goodman et al. 1998; Caselli et al. 2002a). The “coherent core” has subsonic internal motions (see Figure 9), indicating that turbulent motions contribute less to the gas pressure than the thermal component, thus representing a minor contribution to the core support (e.g., Myers 1983; Tafalla et al. 2004). In “coherent cores,” the observed line widths remain approximately constant.

As shown in Section 3.1.4, the turbulent contribution to the line widths increases toward the peripheries in the upper half of the NH$_3$–S core, reaching maximum values in regions exposed the most to the Herbig–Haro jets and outflows that induce turbulence into the environment. This pattern resembles the “transition to coherence” observed in other dense cores. For example, Pineda et al. (2010) report a sharp transition between the coherent core and the more turbulent gas surrounding it in the B5 region in Perseus; in the transition region, the velocity dispersion changes by a factor of 2 over less than a beam width (<0.04 pc). The transition between subsonic and supersonic turbulence has been observed in several other regions covering a range of environments and star formation activities (e.g., Pagani et al. 2010; see also Andrè et al. 2014). In HH 111/HH 121, we can study a dense core in a very violent star formation environment near the Herbig–Haro jets.

The shape and the position of the HH 121 jet with respect to NH$_3$–S poses the interesting question of whether its southern lobe (emanating from VLA-1 at an angle of 15°–20° east with respect to the northern lobe; Gredel & Reipurth 1993) was deflected off the dense material in the core, and as a result, changed its direction toward the west. During such a collision, the jet would have been strongly shocked. Indeed, the knots of the HH 121 jet become strong beyond the area where such a collision would have taken place. The HH 110 jet located to the north of HH 111 is an example of a jet deflected on a dense clump (Reipurth & Olberg 1991; Reipurth et al. 1996). The observational properties of HH 110, such as the morphology and kinematics, are in agreement with the predictions of the analytic and numerical models of jet–cloud collisions (e.g., Raga & Canto 1996; de Gouveia Dal Pino 1999). The models show that the emitting jet knots are still seen as coherent structures after the jet/cloud collision, as observed in HH 121 (e.g., Raga & Canto 1995). A collision between the HH 121 jet with the core is a speculation at this point; a thorough analysis of the geometry and jet proper motions is needed to provide some insight into this possibility.

4.1. Selective Freeze-out

The chemical structure of the NH$_3$–S core shows evidence for “selective” freeze-out, an inherent characteristic of dense cold cores. The abundance of carbon-bearing species such as CO and CS in the dense core centers can be a few orders of magnitude lower than at their edges, while the nitrogen–hydrogen bearing species such as N$_2$D$^+$ and NH$_3$ have a constant or slowly decreasing abundance (e.g., Caselli et al. 1999; Bergin et al. 2001; Bacmann et al. 2002; Caselli et al. 2002b, 2002c; Bergin & Tafalla 2007). These abundance gradients are formed as a result of the gas–grain interactions that dominate the chemistry of the cores and lead to the freeze-out of important gaseous species (e.g., CO) and the subsequent formation of new species in the chemically altered environment. For example, the depletion of CO from the gas phase in the dense core centers leads to the production of species that are normally destroyed by CO, e.g., N$_2$H$^+$ and NH$_3$.

One of the consequences of the CO freeze-out is a great enhancement of the deuterium fractionation, i.e., the ratio of a deuterated species over its counterpart containing H (e.g., Roberts & Millar 2000; Bergin & Tafalla 2007; Busquet et al. 2010). The deuterium fractionation toward HH 111 was...
measured by Hatchell (2003) using the \([\text{NH}_2\text{D}]/[\text{NH}_3]\) ratio. Hatchell (2003) report spectroscopic observations centered on the source VLA-1 in HH 111 (and several other protostellar cores) of the NH$_3$ (1, 1)–(4, 4) lines with the Effelsberg 100 m telescope (HPBW~37") and the NH$_2$D 1$_{11}$–1$_{10}$ line with the IRAM 30 m telescope (HPBW~28"). They only detected the main hyperfine lines for NH$_3$ (1, 1) \( (V_{\text{LSR}} = 8.5 \text{ km s}^{-1}) \) and NH$_2$D toward HH 111. Adopting the rotational temperature of 14.6 K derived for another source in Orion and correcting for different beam areas of the NH$_2$D and NH$_3$ observations, they derived the \([\text{NH}_2\text{D}]/[\text{NH}_3]\) ratio for HH 111 of 11%. This value is much higher than 10$^{-5}$, the elemental value in the interstellar medium within the ∼10 K gas (e.g., Watson 1974; Oliveira et al. 2003). The high value of deuterium fractionation determined based on single-dish spectroscopic observations indicate the presence of dense cold material with depletion due to freeze-out in the HH 111/HH 121 protostellar system. The ALMA interferometric observations revealed the location of these regions.

The chemistry of the dense cores changes with its evolution. The effects of freeze-out are not important for less evolved starless cores when the density is less than a few times 10$^4$ cm$^{-3}$ (see, e.g., Bergin & Tafalla 2007). At this time, the emission from molecules such as CO, C$^{18}$O, CS, and HCO$^+$ can be observed throughout the core. For more evolved sources, when the density is higher than a few times 10$^4$ cm$^{-3}$, the CO is frozen-out in the core center, and nitrogen-bearing species (e.g., N$_2$H$^+$ and NH$_3$) become the best molecular tracers of the core gas. With the CO frozen-out in its center, NH$_3$–S seems to be at a later stage of starless core evolution.

### 4.2. Alfvén Waves

Two intriguing findings from this study are that the N$_2$D$^+$ emission region actually lies at the center of the CO depletion region in NH$_3$–S, displaced from the shell/rim, where \( \sigma_{\text{mH}} = 0 \), and that \( I(\text{N}_2\text{D}^+) \propto \sigma_{\text{mH}} \) (see Figure 16). These observations are consistent with the theoretical predictions for the chemistry in cold gas subject to the passage of magnetohydrodynamic (MHD) waves, presumably related to the existence of MHD turbulence (Charnley 1998). The essential point is that the MHD waves in molecular clouds with the longest lifetimes are Alfvén waves (Arons & Max 1975). In partially ionized molecular clouds, the ion–electron plasma experiences MHD wave perturbations and moves relative to the neutral particles, undergoing collisional damping. The resultant relative ion–neutral streaming (i.e., ambipolar diffusion) imparts additional kinetic energy to collisions involving ions and neutral molecules and so this can nonthermally drive endoergic chemical reactions that would otherwise be inhibited at low temperatures (∼10 K; e.g., Draine 1980).

Low-amplitude Alfvén waves can impart this additional kinetic energy to chemical reactions to drive them without significant gas heating. In particular, the reaction underlying the gas-phase deuteration of interstellar molecules,

\[
\text{H}_3^+ + \text{HD} \rightleftharpoons \text{H}_2\text{D}^+ + \text{H}_2 \rightleftharpoons 225 \text{ K}, \tag{4}
\]

is exothermic in the forward direction and proceeds rapidly at low temperatures. The rate of the reverse process depends on the quantum spin state of the H$_3$ molecules: when they are present in the LTE ortho/para ratio (OPR) of 3:1, then the internal energy of ortho-H$_2$ collisions can drive the reverse reaction at low temperatures (e.g., Pagani et al. 2011). However, in cold molecular clouds, it is expected that most of the H$_2$, formed and ejected from dust grains with an OPR of
will be converted to para-H$_2$ in ion–molecule spin-exchange reactions (Pagani et al. 2011; Wirström et al. 2012). The most direct effect of Alfvén waves connected to MHD turbulence would therefore be the destruction of H$_2$D$^+$ in cold gas and a suppression of the H$_2$D$^+$/H$_3^+$ ratio. However, the most sensitive and easily detectable effect, in the millimeter-wavelength region, is connected to the $^{15}$NHD$_2$/$^{15}$NH$_2$ ratio (Charnley 1998), which is predicted to be suppressed over the ion–neutral collisional damping length, $L_{ni}$, given by

$$L_{ni}[\text{cm}] = 3.45 \times 10^{16} \left( \frac{B}{100 \mu \text{G}} \right) \left( \frac{n_H}{10^4 \text{cm}^{-3}} \right)^{-3/2} \times \left( \frac{x_e}{10^{-7}} \right)^{-1},$$

where $n_H$ is the hydrogen nucleon density, $x_e$ is the fractional ionization, and $B$ is the magnitude of the magnetic field (Markwick et al. 2000).

The VLA-1/VLA-2 region or the HH 111 and HH 121 outflows could be the sources of these putative Alfvén waves. Numerical simulations by De Colle & Raga (2005) show that the ejection of high-density clumps can generate Alfvén waves in the ambient material perpendicular to the direction of the jet motion.

Assuming constant physical conditions between the possible wave sources and NH$_3$–S, we can estimate $L_{ni}$ to see if this is plausible. Taking $x_e = 3 \times 10^{-8}$ and $n_H = 2 \times 10^4 \text{cm}^{-3}$,
typical of dark clouds, and $B = 160 \, \mu G$ at this density (Crutcher 2012), we find $L_{\text{ini}} = 5.86 \times 10^{16}$ cm. The distance between VLA-1 and the 50% of the NH$_3$ (1, 1) emission peak contour in HH 111/HH 121 is 10$''$, which corresponds to $5.98 \times 10^{16}$ cm and so, given the approximations made, VLA-1 could possibly be a source of waves. Alternatively, Figure 10 shows that any waves originating in the HH 121 and HH 111 outflows, and emanating perpendicular to the outflow direction, are closer to 50% of the NH$_3$ emission peak contour and so would indeed impact the regions of NH$_3$–S that show no N$_2$D$^+$ emission. It would be interesting to produce a complementary map of the N$_2$H$^+$ emission to obtain the spatial N$_2$D$^+$/N$_2$H$^+$ to see if it is also inversely proportional to $\sigma_{\text{ini}}$ and test the Alfvén wave scenario further. For sufficiently large amplitudes, such MHD waves will steepen into weak C-shocks, and these can also have observable effects (Pon et al. 2012).

4.3. External Illumination

The high intensity of the NH$_3$ emission from NH$_3$–S suggests that the source may also be affected by the strong
UV radiation from the HH 111 and HH 121 jets. Observational surveys have detected compact regions of enhanced emission (compared to quiescent dark clouds) in several molecules, among them NH$_3$ and HCO$^+$, just ahead of Herbig–Haro objects (e.g., Torrelles et al. 1992; Girart et al. 1994; Girart et al. 1998), as well as along the jets (e.g., Christie et al. 2011). These “externally illuminated clumps” are quiescent, cool ($\sim$10–20 K), have sizes of 10''–20'' (0.019–0.038 pc at 400 pc), and have similar chemical properties. The high molecular abundances from some species found in these clumps (NH$_3$ and HCO$^+$, but also CH$_3$OH, H$_2$CO, SO$_2$, and others) suggest a

Table 4

| Source | $V_{\text{LSR}}$ ($\text{km s}^{-1}$) | $\Delta V_{G}$ ($\text{km s}^{-1}$) | $T_{\text{peak}}$ (K) | $\int T dV$ (K km s$^{-1}$) |
|--------|----------------------------------|----------------------------------|----------------------|-----------------------------|
| Main   | 8.81 ± 0.02                      | 1.07 ± 0.04                      | 0.29 ± 0.02          | 0.40 ± 0.01                 |
| S      | 9.47 ± 0.02                      | 1.00 ± 0.04                      | 0.30 ± 0.02          | 0.39 ± 0.01                 |

Note. $^a$The line width (FWHM) corrected for instrumental broadening, $\Delta V_{G} = \sqrt{\Delta V_{G, \text{obs}}^2 - \Delta V_{G, \text{inst}}^2}$, where $\Delta V_{G, \text{obs}}$ is the observed line width and $\Delta V_{G, \text{inst}}$ is the channel width of 0.65 km s$^{-1}$.
chemical alteration of the high-density quiescent clumps in molecular clouds induced by the radiation generated in the Herbig–Haro shocks (e.g., Girart et al. 1994; Viti & Williams 1999). In this theoretical picture, UV radiation can photodesorb molecules from icy grain mantles containing H2O, NH3, CH4, CH3OH, H2CO, etc. (Boogert et al. 2015), and drive active gas-phase photochemistry. This interpretation is supported by both observations and theoretical models (both static and dynamic, where the radiation source is moving; Taylor & Williams 1996; Christie et al. 2011). Classical examples of externally illuminated clumps are those found near HH1/2 (e.g., Girart et al. 2002), HH 7–11 (e.g., Dent et al. 1993), HH 34 (e.g., Rudolph & Welch 1992), and HH 80N (e.g., Girart et al. 1994, 1998, 2001). Girart et al. (2001) found star formation signatures in the HH 80N dense clump. Unlike NH3–S, these clumps were detected in CO and its isotopologues.

4.4. HCO+ and HCN

We conducted JCMT HCO+ (4–3) and HCN (4–3) observations to test the idea that NH3–S is externally illuminated by the UV radiation from Herbig–Haro objects. Observations of externally illuminated clumps show that the HCO+ emission is enhanced in these regions with line intensities much stronger than expected in quiescent dark emission at this velocity traces the outflow associated with the HH 111 jet, indicating that the HCO+ intensity contrast is difficult. The high spatial and spectral resolution observations with high sensitivity are needed to search for the infall and outflow signatures in NH3–S using HCO+.

Figure 19 shows that the brightest HCO+ emission that can be kinematically associated with NH3–S originates at the eastern peripheries of the source, outside the area with CO depletion (see, e.g., Figure 11). The HCO+ line profile extracted from a single 7″ × 7″ pixel shows signatures of infall—it is self-absorbed and double peaked, with the blue peak brighter than the red peak (see Figure 20 and the middle plot in the left panel in Figure 19). However, these velocity peaks may be two separate velocity components. The origin of the higher velocity component at ∼9.4 km s−1 is uncertain. There is not enough evidence to draw firm conclusions on the presence of infall.

For a comparison, in Figure 24 in Appendix C, we show the HCO+ line profiles for NH3–Main for a grid of 10 × 6 pixels; this area covers the VLA-1 envelope and the base of the outflows (see Figure 17). The HCO+ line profiles show the signatures of infall and outflow. A detailed analysis of the HCO+ and HCN data for NH3–Main is beyond the scope of this paper.

4.5. HCO+/CO Ratio

An interesting fact is that while CO and its isotopologues are clearly depleted in NH3–S and elsewhere, HCO+ emission is nevertheless detectable. Although this may appear counter-intuitive, it can be shown by a simple analysis to be a natural consequence of ion–molecule chemistry (Charnley 1997; see Appendix D). In this case, the HCO+/CO number density ratio is given by

$$\frac{n(HCO^+)}{n(CO)} = \left[ \frac{\alpha}{k_i} \frac{n(CO)}{n_e} \right]^{-1},$$

where n_e is the electron number density, and α and k_i are generic rate coefficients for electron dissociative recombination and proton transfer, respectively.

If we adopt typical 10 K rate coefficients of k_i ≈ 10−9 cm3 s−1 and α ≈ 10−7 cm3 s−1, and taking n_e ∼ 10−3 n(H2), we can identify two limiting cases depending on the n(CO)/n_e ratio. Assuming CO is present at its typical undepleted abundance, where n(CO) ∼ 10−4 n(H2), then n(HCO+)/n(CO) ∼ 10−4, as is typically found. In the case where significant CO depletion has occurred, n(CO) ∼ n_e, n(HCO+)/n(CO) ∼ k_i/α ∼ 10−2. Thus, even when CO is depleted to abundances of ∼10−8 − 10−9, the HCO+ abundance could be in the range ∼10−10 − 10−9 and remain detectable; H3CO+ may therefore also be detectable in NH3–S.

4.6. The Virial Mass

To investigate whether NH3–S is unstable to gravitational collapse, we calculate the virial parameter (α) defined as

$$\alpha = M_{vir}/M, \quad \text{where } M_{vir} \text{ is the virial mass}$$

$$M_{vir} = \frac{5\sigma^2 R}{G},$$

where σ is the velocity dispersion.
(e.g., MacLaren et al. 1988; McKee & Zweibel 1992; Enoch et al. 2008; Kauffmann et al. 2013), and $M$ is the observed source mass. In Equation (7), $\sigma_V$ is the total line width of the molecular gas, $R$ is the radius of the core, and $G$ is the gravitational constant. The total line width is the combination of nonthermal gas motions ($\sigma_{nth}$ calculated from NH$_3$) and the thermal motions of the particle of mean mass ($\sigma_s$ or a thermal sound speed, $c_s$), $\sigma_V = \sqrt{\sigma_{nth}^2 + \sigma_s^2}$. For $R$, we use the “effective radius” (FWHM$_{eff}$/2; see above). To account for the central condensation of the core, $M_{vir}$, calculated using Equation (7), can be divided by a parameter “$a$” given by $a = \left( \frac{p/3}{1-2p/5} \right)$ for a power-law density profile $\rho(r) \propto r^{-p}$. We adopt $p = 1.5$, giving $a = 1.25$. We derive an $M_{vir}$ of 0.75 $M_\odot$ for NH$_3$–S using Equation (7) or 0.6 $M_\odot$ after correcting for non-uniform density profile.

Since the virial parameter is related to the ratio of the kinetic to potential energies, it can be used to assess the stability of the core (see, e.g., Kauffmann et al. 2013 and references therein). For $\alpha \gg 1$, the kinetic energy dominates and clumps/cores will expand and disperse, while those with $\alpha \ll 1$ are often unstable and will likely collapse. The homogeneous and spherical clumps/cores with $\alpha = 1$ are considered gravitationally bound and virialized. In the above estimate of the virial parameter, only the gravity and velocity dispersion are considered. The external pressure that may confine the clumps or magnetic fields that can support the cores against self-gravity is neglected.

For NH$_3$–S, we derive the virial parameter $\alpha$ of 2.5 using an $M_{vir}$ of 0.75 $M_\odot$ and the observed mass $M$ of 0.3 $M_\odot$ derived from the NH$_3$ data. Theoretical models show that nonmagnetized clumps/cores with $\alpha \lesssim 2$ are gravitationally bound (e.g., Bertoldi & McKee 1992; Kauffmann et al. 2013). Due to the large uncertainties of the virial parameter estimation, it is not clear whether NH$_3$–S is a marginally gravitationally bound or unbound (pressure-confined) starless core. The observations (e.g., Tachihara et al. 2002; Morata et al. 2005) and theoretical results (e.g., Klessen et al. 2005 for the turbulent fragmentation model) indicate that starless cores have virial masses larger than their actual masses or are near equipartition (e.g., Caselli et al. 2002a). The models show that gravitationally unbound cores may still collapse if they are compressed by turbulence (e.g., Gómez et al. 2007).

5. Summary and Conclusions

We present the results of VLA NH$_3$ (1, 1) and (2, 2) observations of HH 111/HH 121, combined with the analysis of JCMT HCO$^+$ and HCN observations, and archival ALMA $^{13}$CO, $^{12}$CO, C$^{18}$O, N$_2$D$^+$, and $^{13}$CS data. We detected two ammonia sources in HH 111/HH 121. One of the ammonia sources (NH$_3$–Main) is associated with HH 111 and traces the envelope of the protostar that is the source of the Herbig–Haro jet. The second ammonia source (NH$_3$–S) located $\sim 15''$ ($\sim 0.03$ pc) toward the southeast is a new detection. The HH 111/HH 121 protostellar system and its surroundings have been
thoroughly covered by the observations from optical to centimeter wavelengths, yet NH$_3$–S remained undetected until our NH$_3$ observations.

We use the NH$_3$ data to derive the kinematic and physical properties of NH$_3$–Main and NH$_3$–S, including the velocity and velocity dispersion, the kinetic temperature, excitation temperature, NH$_3$ column density, and mass. NH$_3$–Main and NH$_3$–S are two distinct velocity components with the NH$_3$ line-center velocities separated by $\approx 1$ km s$^{-1}$. The reason for multiple velocity components in a single region (also observed toward other protostars) could be related to the initial conditions in the clouds in agreement with the theory of gravoturbulent star formation.

The carbon-bearing molecular emission traces the envelope and disk of the central source VLA-1 and the molecular outflows associated with the HH 111 and HH 121 jets, i.e., the region coinciding with NH$_3$–Main. No C$^{18}$O, $^{12}$CO, and $^{13}$CO emission are detected in the center of NH$_3$–S. However, the $^{13}$CO and C$^{18}$O emission wraps around the source roughly from east to west along its northern rim. The $^{13}$CS emission is confined to the envelope of VLA-1.

There are two N$_2$D$^+$ condensations in HH 111/HH 121. One of the condensations is located in NH$_3$–Main. The second N$_2$D$^+$ condensation is associated with NH$_3$–S with the peak N$_2$D$^+$ emission coinciding with the peak of the NH$_3$ emission. The observable abundances of N$_2$D$^+$ can only be achieved in the coldest and densest molecular cores where CO is frozen-out onto dust grains. A nondetection of CO in the center of NH$_3$–S provides evidence for this “selective” freeze-out, which is an inherent property of dense cold cores.

Based on the ammonia data, we determined the turbulent velocity dispersions in the region. In NH$_3$–Main, the turbulent velocity dispersion is supersonic close to the protostar VLA-1, which is the source of the jet, indicating that the jet is interacting with the envelope material. NH$_3$–S has subsonic internal motions and roughly constant observed line widths, consistent with it being a “coherent core.”

Two interesting results of this study are that the N$_2$D$^+$ emission region lies at the center of the CO depletion region in NH$_3$–S, displaced from the rim where the nonthermal velocity dispersion is enhanced, and that the intensity of the N$_2$D$^+$ emission is inversely proportional to the nonthermal velocity dispersion. These observations are consistent with the theoretical predictions for the chemistry in cold gas subject to the passage of MHD waves, presumably related to the existence of MHD turbulence. The MHD waves in molecular clouds with the longest lifetimes are Alfvén waves, which can be generated by the HH 111 and HH 121 outflows in the direction perpendicular to the jet motion and impact the regions of NH$_3$–S that show no N$_2$D$^+$ emission.

Another interesting fact is that while CO and its isotopologues are clearly depleted in NH$_3$–S and elsewhere, HCO$^+$ emission is nevertheless detectable. We show that it is a natural consequence of ion–molecule chemistry. We also investigated the possibility that NH$_3$–S is an externally illuminated clump. The detection of faint HCO$^+$ emission toward NH$_3$–S in our JCMT observations is not consistent with the predictions of theoretical models of external illumination by strong ultraviolet radiation.

The physical and chemical properties of NH$_3$–S, the fact that it is located in the dark cloud and there is no indication of the presence of a central object, suggest that NH$_3$–S is a starless core. The environment of the core is turbulent, with the turbulence induced by two Herbig–Haro jets and associated outflows, and may be an important factor in the core’s formation and evolution. Based on the currently available data, we cannot fully explain the nature of NH$_3$–S. For example, it remains unclear why NH$_3$–S has not been detected in the far-infrared to millimeter continuum observations. Further molecular line observations and very high sensitivity submillimeter/millimeter continuum observations are essential to gain more insight into the nature of NH$_3$–S and on the interaction between Herbig–Haro jets and nearby dense cores. Starless core studies provide a great opportunity to determine the initial conditions of star formation.

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**Appendix A**

**ALMA Science Data Model UIDs**

The complete list of ALMA Science Data Model (ASDM) UIDs used is as follows: uids://A002/X7f18bf/X72, uids://A002/X7f9c9da/X27a1, uids://A002/X7ecbf/x666, uids://A002/X75ab74/X1f14, uids://A002/X75ab74/Xeb1, uids://A002/X75ab/bf/X1130, uids://A002/X75ab/fb/X9a8, uids://A002/X75ab/bf/X9de, uids://A002/X78774a/X842, uids://A002/X788be1/X438, uids://A002/X78e6fe/X3c7, uids://A002/X78e6fe/X68, uids://A002/X7f9c9da/X2d75, uids://A002/X7f9c9da/X5642, uids://
Appendix B

The ALMA C¹⁸O and ¹³CO Channel Maps

We present the figures showing the ALMA C¹⁸O (2–1) channel maps (Figure 21) and the C¹⁸O (2–1)/¹³CO (2–1) channel maps combined with the NH₃ (1, 1) channel maps for the corresponding LSR velocities and the Spitzer 4.5 μm image (Figures 22/23). The figures are described in detail in Section 3.2.

Appendix C

The HCO⁺ (4–3) Line Profiles for HH 111/NH₃-Main

In Figure 24, we present the JCMT HCO⁺ (4–3) line profiles for HH 111 that corresponds to the ammonia source NH₃-Main. Figure 24 shows the HCO⁺ spectra for the individual pixels enclosed in the orange rectangle in Figure 17. The figure is briefly discussed in Section 4.4.

Appendix D

The HCO⁺/CO Number Density Ratio

We follow the analytic treatment of Charnley (1997). Cosmic-ray ionization of H₂ produces H⁺, at a rate of ζ ionizations s⁻¹, which then forms HCO⁺ and N₂H⁺ by proton transfers to CO and N₂. N₂H⁺ is also destroyed by proton transfer to CO. We assume a generic rate k_i for these processes. The three molecular ions are then assumed to undergo electron dissociative recombination (neglecting recombination on negatively charged dust grains) at rates α₃ for H₂⁺, and α for CO and N₂. The number density of HCO⁺ in steady state is then

\[ n(\text{HCO}^+) = \frac{k_i n(\text{H}^+)}{\alpha n_e} n(\text{CO}). \]  

(8)

If all atomic oxygen is frozen-out on grains as water ice, then

\[ n(\text{H}_2^+) = \frac{\zeta n(\text{H}_2)}{k_i n(\text{CO}) + k_i n(\text{N}_2) + \alpha_3 n_e}. \]  

(9)

\[ n(\text{N}_2^+) = \frac{k_i n(\text{H}_2^+) n(\text{N}_2)}{k_i n(\text{CO}) + \alpha n_e}. \]  

(10)

Substituting for \( n(\text{H}_2^+) \) and \( n(\text{N}_2^+) \) in Equation (8), we obtain

\[ n(\text{HCO}^+) = \frac{k_i n(\text{H}_2)}{\alpha_3 n_e + k_i n(\text{CO}) + k_i n(\text{N}_2)} \times \frac{n(\text{CO})}{\alpha n_e + k_i n(\text{CO})}. \]  

(11)

Now assuming \( \alpha_3 = \alpha \) and making use of the result that the total electron number density \( n_e \) is given by

\[ n_e^2 = \frac{\zeta n(\text{H}_2)}{\alpha}. \]  

(12)

The total electron number density \( n_e \) is given by

\[ \frac{n(\text{HCO}^+)}{n(\text{CO})} = \frac{k_i n_e}{\alpha n_e + k_i n(\text{CO})} = \frac{1}{\alpha} + \frac{n(\text{CO})}{n_e}. \]  

(13)

ORCID iDs

Marta Sewilo https://orcid.org/0000-0003-2248-6032
Jennifer Wiseman https://orcid.org/0000-0002-1143-6710
Renny Indebetouw https://orcid.org/0000-0002-4663-6827
Steven B. Charnley https://orcid.org/0000-0001-6752-5109
Jaime E. Pineda https://orcid.org/0000-0002-3972-1978
Johan E. Lindberg https://orcid.org/0000-0003-8311-4591
Sheng-Li Qin https://orcid.org/0000-0003-2302-0613

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