IRAM-PdBI OBSERVATIONS OF BINARY PROTOSTARS. I. THE HIERARCHICAL SYSTEM SVS 13 IN NGC 1333

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ABSTRACT

We present millimeter (mm) interferometric observations of the young stellar object SVS 13 in NCG 1333 in the \(\text{N}_2\text{H}^+\) \((1-0)\) line and at 1.4 mm and 3 mm dust continuum, using the IRAM Plateau de Bure interferometer. The results are complemented by infrared data from the Spitzer Space Telescope. The mm dust continuum images resolve four sources (A, B, C, and VLA 3) in SVS 13. With the dust continuum images, we derive gas masses of 0.2–1.1 \(M_\odot\) for the sources, \(\text{N}_2\text{H}^+\) \((1-0)\) line emission is detected and spatially associated with the dust continuum sources B and VLA 3. The observed mean line width is \(\sim 0.48\text{ km s}^{-1}\) and the estimated virial mass is \(\sim 0.7\text{ M}_\odot\). By simultaneously fitting the seven hyperfine line components of \(\text{N}_2\text{H}^+\), we derive the velocity field and find a symmetric velocity gradient of \(\sim 28\text{ km s}^{-1}\) pc\(^{-1}\) across sources B and VLA 3, which could be explained by core rotation. The velocity field suggests that sources B and VLA 3 are forming a physically bound protobinary system embedded in a common \(\text{N}_2\text{H}^+\) core. Spitzer images show mid-infrared emission from sources A and C, which is spatially associated with the mm dust continuum emission. No infrared emission is detected from source B, implying that the source is deeply embedded. Based on the morphologies and velocity structure, we propose a hierarchical fragmentation picture for SVS 13 where the three sources (A, B, and C) were formed by initial fragmentation of a filamentary prestellar core, while the protobinary system (sources B and VLA 3) was formed by rotational fragmentation of a single collapsing subcore.

Key words: binaries: general – ISM: individual (SVS 13, HH 7-11) – ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. INTRODUCTION

Although both observations and theoretical simulations support the hypothesis that the fragmentation of collapsing protostellar cores is the main mechanism for the formation of binary/multiple stellar systems, many key questions concerning this fragmentation process, e.g., the exact \textit{when}, \textit{where}, \textit{why}, and \textit{how}, are still under debate (see reviews by Bodenheimer et al. 2000; Tohline 2002; Goodwin et al. 2007). To answer these questions, direct observations of the earliest embedded phase of binary star formation are needed to study in detail their kinematics. This was unfortunately long hampered by the low angular resolution of millimeter (mm) telescopes. However, the recent availability of large mm interferometers has enabled us to directly observe the formation phase of binary stars, although the number of known and well studied systems is still very small (see Launhardt 2004).

To search for binary protostars and to derive their kinematic properties, we have started a systematic program to observe, at high angular resolution, a number of isolated low-mass (pre-) protostellar molecular cloud cores. The initial survey was conducted at the Owens Valley Radio Observatory (OVRO) mm-wave array (Launhardt 2004; Chen et al. 2007, hereafter Paper I; R. Launhardt et al. 2009, in preparation), and is now continued with the Australia Telescope Compact Array (ATCA; Chen et al. 2008b, hereafter Paper II), the Submillimeter Array (SMA; Chen et al. 2008a), and the IRAM Plateau de Bure Interferometer (PdBI) array (this work and X. Chen et al. 2009, in preparation).

SVS 13 is a young stellar object (YSO) located in the NGC 1333 star-forming region at a distance of 350 pc\(^1\) (Herbig & Jones 1983). It was discovered as a near-infrared (NIR) source by Strom et al. (1976). At least three mm continuum sources were detected around SVS 13 (Chini et al. 1997; Bachiller et al. 1998, hereafter B98) and named A, B, and C, respectively (Looney et al. 2000, hereafter LMW2000). Source A is coincident with the infrared/optical source SVS 13, source B is located \(\sim 15''\) southwest of A, and source C is further to the southwest (B98; LMW2000). With BIMA observations, LMW2000 detected another mm source located \(\sim 6''\) southwest of source A, which is coincident with the radio source VLA 3 in the VLA survey of this region (Rodríguez et al. 1997; 1999). More recently, Anglada et al. (2000, 2004) revealed that source A is actually a binary system with an angular separation of \(0'\). Located to the southeast of SVS 13 is the well known chain of Herbig–Haro (HH) objects 7–11 (Herbig 1974; Strom et al. 1974; Khanzadyan et al. 2003 and references therein). Although several possible driving candidates have been proposed for this large-scale HH chain (e.g., Rodríguez et al. 1997), high-resolution CO (2–1) observations (Bachiller et al. 2000, hereafter B2000), as well as an analysis of the spectral energy distributions (LMW2000), clearly favor SVS13 A as the driving source. In this paper, we present our IRAM-PdBI observations in the \(\text{N}_2\text{H}^+\) \((1-0)\) line and at the 1.4 mm and 3 mm dust continuum toward SVS 13, together with complementary infrared data from the Spitzer Space Telescope (hereafter \textit{Spitzer}). In Section 2, we describe the observations and data reduction; observational results are presented in Section 3 and discussed in Section 4. The main conclusions of this study are summarized in Section 5.

\(^1\) Although recent VLBA observations suggest a distance of 220 pc (see Hirota et al. 2007), we use here 350 pc for consistency with earlier papers.
Figure 1. IRAM-PdBI mm dust continuum images of SVS 13. Contours start at \(\sim 3\sigma\) (see Table 1) by steps of \(\sim 2\sigma\). Crosses in the images mark the position of the radio source VLA 3 (Rodríguez et al. 1997). The synthesized PdBI beam is shown as grey oval in the images.

Table 1

| Object Name | Other Name | R.A. & Decl. (J2000) | Distance (pc) | Array | HPBW\(^a\) (arcsec) | RMS\(^b\) (mJy beam\(^{-1}\)) |
|-------------|------------|----------------------|---------------|-------|----------------------|-----------------------------|
| SVS13       | HH 7 – 11  | 03:29:03.20, 31:15:56.00 | 350 | CD | 2.8 \times 2.5, 1.2 \times 1.1 | 15.5, 0.62, 3.7 |

Notes.

\(^a\) Reference position for figures and tables in the paper.

\(^b\) Naturally weighted synthesized FWHM beam sizes at 3 mm and 1.4 mm dust continuum.

\(^c\) 1\(\sigma\) noises at \(N_2H^+ (1–0)\) line, 3 mm dust continuum, and 1.4 mm dust continuum.

2. OBSERVATIONS AND DATA REDUCTION

2.1. IRAM PdBI Observations

Millimeter interferometric observations of SVS 13 were carried out with the IRAM\(^2\) PdBI in 2006 March (C configuration with six antennas) and July (D configuration with five antennas). The 3 mm and 1 mm bands were observed simultaneously, with baselines ranging from 16 m to 176 m. During the observations, two receivers were tuned to the \(N_2H^+ (1–0)\) line at 93.1378 GHz and the \(^13\)CO (2–1) line at 220 GHz, respectively. Bandwidths in the \(N_2H^+\) line and \(^13\)CO line were 20 MHz and 40 MHz, resulting in channel spacings of 39 kHz and 79 kHz and velocity resolutions of 0.2 km s\(^{-1}\) and 0.1 km s\(^{-1}\), respectively. The remaining windows of the correlator were combined to observe the dust continuum emission with a total bandwidth of 500 MHz at both \(\lambda\) 3 mm and \(\lambda\) 1.4 mm. System temperatures of the 3 mm and 1 mm receivers were typically 110–200 K and \(\sim 300\) K, respectively. The (naturally weighted) synthesized half-power beam widths were 2\(\prime\)\(^\prime\) 8 \times 2\(\prime\)\(^\prime\) 5 at 93.2 GHz and 1\(\prime\)\(^\prime\) 2 \times 1\(\prime\)\(^\prime\) 1 at 220 GHz. The FWHM primary beams were \(\sim 54\)\(\prime\)\(^\prime\) and 23\(\prime\)\(^\prime\), respectively. Several nearby phase calibrators were observed to determine the time-dependent complex antenna gains. The correlator bandpass was calibrated with the sources 3C273 and 1749 + 096, while the absolute flux density scale was derived from 3C345. The flux calibration uncertainty was estimated to be \(\sim 15\%\). Only \(N_2H^+\) line data were used here because the signal-to-noise ratio of the \(^13\)CO line data was much lower in the 3 mm observational conditions, although the quality of the 1.4 mm dust continuum data is sufficient for our science goals. The data were calibrated and reduced using the GILDAS\(^3\) software. Observing parameters are summarized in Table 1.

2.2. Spitzer Observations

Mid-infrared data were obtained from the Spitzer Science Center.\(^4\) SVS 13 was observed by Spitzer on 2004 September 8 with the Infrared Array Camera (IRAC; AOR key 5793280) and 2004 September 20 with the Multiband Imaging Photometer for Spitzer (MIPS; AOR key 5789440). The source was observed as part of the c2d Legacy program (Evans et al. 2003). The data were processed by the Spitzer Science Center using their standard pipeline (version S14.0) to produce Post-Basic Calibrated Data (P-BCD) images, which are flux-calibrated into physical units (MJy sr\(^{-1}\)). Further analysis and figures were completed with the IRAF and GILDAS software packages.

3. RESULTS

3.1. IRAM-PdBI Results

3.1.1. Millimeter Dust Continuum Emission

The 3 mm dust continuum image (see Figure 1) shows three distinct sources in SVS 13. Following LMW2000, the sources are labeled A, B, and C, respectively. Source C, the weakest one, lies outside the field of view at 1.4 mm. The large-scale common envelope of the three sources, detected in the submillimeter (sub-mm) (Chandler & Richer 2000) and mm (Chini et al. 1997) single-dish maps, is resolved by the interferometer at 3 mm and 1.4 mm. From Gaussian \(uv\) plane fitting, we derive flux densities and FWHM sizes of the sources (see Table 2). The measured angular separations are 14\(\prime\) 6 \pm 0\(\prime\) 2 between sources A and B and 19\(\prime\) 8 \pm 0\(\prime\) 2 between B and C. A weak emission peak, spatially coincident with the radio source VLA 3 (Rodríguez et al. 1997) and the 2.7 mm dust continuum source A2 (LMW2000), is detected in the 3 mm dust continuum image, but not seen in the higher-resolution 1.4 mm image.

\(^2\) IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

\(^3\) http://www.iram.fr/IRAMFR/GILDAS

\(^4\) http://ssc.spitzer.caltech.edu
The contour shows an approximate size of the large-scale common envelope. The direction of blue and redshifted outflows (see B98 and B2000). Dashed elliptical lines mark the peaks of 3 mm dust continuum emission. Solid and dashed arrows show the velocity field of SVS 13 (see Figure 4). The outflow information from B98 and B2000, together with outflow information from BIMA + FCRAO N2H+ image of NCG 1333 (see Walsh et al. 2007), and may be the remnant of a large-scale N2H+ envelope (see Section 4.4). Figure 2 shows the velocity-integrated N2H+ intensity image of SVS 13, together with outflow information from B98 and B2000. The emission was integrated over all seven components of the N2H+ line with frequency masks that completely cover velocity gradients within the object. An N2H+ core, spatially associated with the mm continuum sources B and VLA 3, is found in the image. The core is elongated in the northeast–southwest direction and double-peaked: one peak is coinciding with source B and the other is located ~ 2″ southwest to VLA 3. The FWHM radius of the whole core is measured to be ~ 1520 AU. A jet-like extension is seen at the western edge of the core, which is ~ 10″ in length and extending to the north. Three smaller clumps (at ~ 3−4 σ level), one located close to source C and the other two located ~ 10′′ northeast of source A, are also seen in the image. We note that the small clumps towards northeast of source A are also seen in the BIMA + FCRAO N2H+ image of NCG 1333 (see Walsh et al. 2007), and may be the remnant of a large-scale N2H+ envelope (see Section 4.4).

Figure 3 shows the N2H+ (1−0) spectra at the two peak positions. All seven hyperfine lines of N2H+ (1−0) have been detected. Using the hyperfine fitting program in CLASS, we derive the mean core velocity (VLSR), intrinsic line widths (Δν), total optical depth (τtot), and excitation temperatures (Tex) (see Table 3).

By simultaneously fitting the seven hyperfine components with the routine described in Paper I, we derive the mean velocity field of SVS 13 (see Figure 4). The outflow information (from B98) is also shown in the map. SVS 13 shows a well-orderd velocity field, with a smooth gradient from southwest to northeast. A least-squares fitting of the velocity gradient has been performed with the routine described in Goodman et al. (1993) and provides the following results: the mean core velocity is ~ 8.6 km s−1, the velocity gradient is 28.0 ± 0.1 km s−1 pc−1, and the position angle (P.A.) of the gradient is 51.3 ± 0.2 degree. The details of the velocity field are discussed in Section 4.2. Figure 5 shows the spatial distribution of the N2H+ line widths in the map. We find that the line widths are roughly constant within the core and large line widths are mainly seen in the gap (see Figure 1). Hereafter, we refer to this weak 3 mm continuum source as VLA 3.

Assuming that the mm dust continuum emission is optically thin, the total gas mass in the circumstellar envelope was calculated with the same method described in Launhardt & Henning (1997). In the calculations, we adopt an interstellar hydrogen-to-dust mass ratio of 110 (Draine & Lee 1984) and a factor of 1.36 accounting for helium and heavier elements. For all sources, we use mass-averaged dust temperature and opacity of $T_d = 20$ K and $\kappa_{1.3\, \text{mm}} = 0.8$ cm$^2$ g$^{-1}$ (a typical value suggested by Ossenkopf & Henning 1994 for coagulated grains in protostellar cores), respectively. From the 1.4 mm dust continuum image, the total gas masses of sources A and B are estimated to be 0.75 ± 0.12 $M_\odot$ and 1.05 ± 0.16 $M_\odot$, respectively. The gas masses estimated from the 3 mm dust continuum image are consistent with those derived from the 1.4 mm image with a dust spectral index of $\beta = 0.5$ ($\kappa_\nu \propto \nu^{\beta}$). We note that this index is slightly smaller than the typical $\beta = 1$, but agrees with values for beta found in other highly embedded objects (see Ossenkopf & Henning 1994).

Table 2

| Source | Position | $S_{\nu}^{a,b}$ (mJy) | FWHM sizes at 3 mm | $M_{\text{gas}}$ |
|--------|----------|------------------------|--------------------|---------------|
| SVS 13 |          |                        |                    |               |
| A      | 03:29:03.75 | 31:16:03.76          | 30.0 ± 4.5         | 135 ± 21      |
| B      | 03:29:03.07 | 31:15:52.02          | 42.4 ± 6.4         | 193 ± 30      |
| C      | 03:29:01.96 | 31:15:38.26          | 6.5 ± 1.0          | -             |

Table 3

| Peak | VLSR (km s$^{-1}$) | Δν (km s$^{-1}$) | τtot | Tex (K) |
|------|--------------------|-----------------|------|---------|
| (2, 4)| 8.90 ± 0.01        | 0.31 ± 0.01     | 1.9 ± 0.1 | 11.3 ± 0.5 |
| (−2, −4)| 8.39 ± 0.01       | 0.46 ± 0.02     | 2.2 ± 0.1 | 10.1 ± 0.5 |

Note. a Value at the two intensity peaks. The error represents 1σ error in the hyperfine fitting.

3.1.2. N2H+ (1−0) Emission

(see Figure 1). Hereafter, we refer to this weak 3 mm continuum source as VLA 3.

Assuming that the mm dust continuum emission is optically thin, the total gas mass in the circumstellar envelope was calculated with the same method described in Launhardt & Henning (1997). In the calculations, we adopt an interstellar hydrogen-to-dust mass ratio of 110 (Draine & Lee 1984) and a factor of 1.36 accounting for helium and heavier elements. For all sources, we use mass-averaged dust temperature and opacity of $T_d = 20$ K and $\kappa_{1.3\, \text{mm}} = 0.8$ cm$^2$ g$^{-1}$ (a typical value suggested by Ossenkopf & Henning 1994 for coagulated grains in protostellar cores), respectively. From the 1.4 mm dust continuum image, the total gas masses of sources A and B are estimated to be 0.75 ± 0.12 $M_\odot$ and 1.05 ± 0.16 $M_\odot$, respectively. The gas masses estimated from the 3 mm dust continuum image are consistent with those derived from the 1.4 mm image with a dust spectral index of $\beta = 0.5$ ($\kappa_\nu \propto \nu^{\beta}$). We note that this index is slightly smaller than the typical $\beta = 1$, but agrees with values for beta found in other highly embedded objects (see Ossenkopf & Henning 1994).

5 To approximately correct the derived masses for the actual dust temperature, the mass has to be scaled with $T_d(\text{adopted})/T_d$ for $T_d > 20$ K. This also means that the derived masses are not very sensitive to the adopted temperature in the range between 20 and 50 K.
between the two emission peaks and the jet-like extension at the core edge. The mean line width (0.48 ± 0.01 km s⁻¹) is derived from Gaussian fitting to the distribution of line widths versus solid angle area (see Figure 6). The virial mass of the N₂H⁺ core is then estimated to be 0.7 ± 0.1 M☉, using the same method described in Paper II. The derived virial mass is slightly smaller than but still comparable to the total gas mass derived from the mm dust continuum images for source B.

3.2. Spitzer Results

Figure 7 shows the Spitzer images of SVS 13. In a wide-field IRAC 2 (4.5 μm) image shown in Figure 7(a), a number of HH objects are seen, implying active star formation in the NGC 1333 region. The HH objects that can be clearly distinguished are labeled by the same numbers as in Bally et al. (1996; for a comparison see optical image in their Figure 2). Figures 7(b) and 7(c) show enlarged views of the 4.5 μm image, overlaid with the contours from the PdBI 3 mm dust continuum and N₂H⁺ images. In the IRAC maps, a strong infrared source is spatially coincident with the dust continuum source A. Located to the southeast of source A is the well-known HH chain 7–11 (see Figure 7(b)), which is associated with a high-velocity blue-shifted CO outflow (B2000). Another collimated jet is found in the southern part of SVS 13 with the continuum source C being located at the apex (see Figure 7(b)), but no NIR source is found at this position. Figure 7(c) shows that the N₂H⁺ emission is not spatially associated with the infrared emission from source A, but extends roughly perpendicular to the directions of the jets/outflows.

In the MIPS 1 (24 μm) image, a strong infrared source (saturated in the image) is again found at the continuum source A, and another weak one is found at source C. In the MIPS 2 (70 μm) image, extended emission are seen at both sources A and C. It should be noted that no infrared emission is detected from source B in any IRAC or MIPS bands, suggesting that this source is a deeply embedded object. Flux densities of sources A and C are measured with aperture photometry in...
Figure 7. Spitzer images of SVS 13. (a) Spitzer IRAC band 2 (4.5 μm) image of SVS 13 (reference position at R.A. = 03:29:17.49, decl. = 31:12:48.54, J2000); (b) IRAC band 2 image overlaid with the PdBI 3 mm dust continuum contours; (c) same as Figure 7(b), but overlaid with the PdBI N$_2$H$^+$ intensity contours; (d) Spitzer MIPS 1 (24 μm) image of SVS 13, overlaid with the PdBI 3 mm dust continuum contours; (e) same as Figure 7(d), but for Spitzer MIPS 2 (70 μm) image.

4. DISCUSSION

4.1. Spectral Energy Distributions and Evolutionary Stages

Figure 8 shows the spectral energy distributions (SEDs) of SVS 13 A, B, and C. IRAS far-infrared (only 100 μm data are used here) data are adopted from Jennings et al. (1987); SCUBA sub-mm data from Chandler & Richer (2000); IRAM-30 m 1.3 mm data from Chini et al. (1997); BIMA 2.7 mm data from LMW2000; IRAM PdBI 3.1 mm data from this work and 3.5 mm data from B98. Since IRAS could not resolve SVS 13, the 100 μm flux ratio of A : B : C = 8:1:1 was inferred from the ratios at other wavelengths. For source B, the Spitzer sensitivities at IRAC bands (also for source C) and MIPS bands are adopted.7 In order to derive luminosities and temperatures, we first interpolated and then integrated the SEDs, always assuming spherical symmetry. Interpolation between the flux densities was done by a χ$^2$ single-temperature grey-body fit to all points at λ ≥ 100 μm, using the method described in Paper II. A simple logarithmic interpolation was performed between all points at λ ≤ 100 μm. The fitting results are listed in Table 5.

The fitting results of sources B and C confirm the earlier suggestion (see, e.g., Chandler & Richer 2000) that they are Class 0 protostars. For source A, the high bolometric temperature (∼ 114 K) and low $L_{\text{submm}}/L_{\text{bol}}$ ratio (∼ 0.8%) suggest it is a

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6 We use the single-dish fluxes because the interferometric 1.3 mm (B98) and 1.4 mm (this work) data do not recover the envelope fluxes.

7 see http://ssc.spitzer.caltech.edu/irac/sens.html and http://ssc.spitzer.caltech.edu/mips/sens.html
Figure 8. Spectral energy distributions of SVS 13 A (left), B (middle), and C (right). Error bars (1σ) are indicated for all data points, but are mostly smaller than the symbol sizes. While most solid squares represent real observational data points, the 2.7–3.5 mm fluxes were measured from interferometric maps which resolved out the envelope and thus represent lower limits only. Open squares represent IRAS 100 μm data points, where flux densities are estimated for the three sources with ratios assumed in Section 4.1. Open triangles represent the sensitivities of IRAC and MIPS. Solid lines show the best fit for all points at λ ≥ 100 μm using a grey-body model (see text). Dashed lines at λ ≤ 100 μm show the simple logarithmic interpolation used to derive the luminosity. The fitting results are summarized in Table 5.

Table 4

| Source | R.A. a | Decl. a | S(3.6 μm) | S(4.5 μm) | S(5.8 μm) | S(24 μm) | S(70 μm) |
|--------|--------|---------|-----------|-----------|-----------|----------|----------|
| SVS 13 A | 03:29:03.73 | 31:16:03.80 | 292 ± 20 | 499 ± 44 | 2470 ± 140 | 2330 ± 100 | > 21 |
| C       | 03:29:01.98 | 31:15:38.17 | < 0.36b  | < 0.43b   | < 1.3b    | < 0.54b  | 0.22 ± 01 | > 12    |

Notes.

a Peak positions measured at IRAC band 3 (for SVS 13 A) and MIPS band 1 (for SVS 13 C).
b Spitzer IRAC sensitivities.

Table 5

| Source | T_dust (K) | T_turb (K) | L_dust (L_⊙) | L_turb (L_⊙) | L_dust/L_turb (%) | Class               |
|--------|------------|------------|---------------|--------------|-------------------|---------------------|
| SVS 13 A | 33 | 114 | 46.6 | 0.37 | 0.8 | 0/I (?) |
| B       | 22 | 28 | 5.6  | 0.28 | 5.0 | 0      |
| C       | 20 | 36 | 4.9  | 0.13 | 2.7 | 0      |

Class I young stellar object. Nevertheless, we want to note that source A resembles a Class 0 protostar at least two aspects: (1) it is associated with a cm radio source (VLA 4; Rodríguez et al. 1999) and embedded in a large-scale dusty envelope, and (2) it is driving an extremely high velocity CO outflow (B2000), which is believed to be one of the characteristics of Class 0 protostars (see Bachiller 1996). We speculate that source A could be a Class 0/I transition object, which is visible at infrared wavelengths due to the high inclination angle (see B2000).

4.2. Gas Kinematics of the N2H+ Core

4.2.1. Turbulence

Assuming that the kinetic gas temperature is equal to the dust temperature (≈ 20 K; see Table 5), the thermal line widths of N2H+ and an “average” particle of mass 2.33 m_H (assuming gas with 90% H2 and 10% He) are ≈ 0.18 km s⁻¹ and ≈ 0.62 km s⁻¹, respectively. The latter line width represents the local sound speed. The nonthermal contribution to the N2H+ line width (∆νNT = √(∆νΔν_m - ∆νΔν_s²) is then estimated to be ≈0.44 km s⁻¹, which is about twice times larger than the thermal line width, but smaller than the specific angular momentum J/M is calculated to be 0.47 × 10⁻³ km s⁻¹ pc (1.45 × 10¹⁶ m² s⁻¹), using the same method as described in Paper II. The ratio of the rotational...
energy to the gravitational potential energy is also calculated with the same method as described in Paper II, and the estimated $\beta_{\text{rot}}$ value is $\sim 0.025$ (uncorrected for inclination angle).

### 4.3. SVS 13 B and VLA 3: A Bound Protobinary System

Our observations show a weak 3 mm dust continuum source at the position of the radio source VLA 3 (see Figure 1). This dust continuum source is embedded in the elongated $N_2H^+$ core together with source B (see Figure 2). The angular separation and flux ratio between sources B and VLA 3 are measured to be $10.7 \pm 0.2$ and $\sim 13$ from the 3 mm dust continuum image, respectively.

The velocity field map shows a clear velocity gradient across the two sources, with sources VLA 3 and B being located in the red and blueshifted regions, respectively. As discussed above, we assume that this systematic velocity gradient is due to the core rotation. The two sources are thus probably forming a protobinary system that has originated from rotational fragmentation of the core that we now observe in the $N_2H^+$ line.

Figure 9 shows a position–velocity diagram, along the connecting line between sources B and VLA 3. The radial velocity difference between the two sources is $\sim 0.5 \text{ km s}^{-1}$. Assuming that the two sources are in Keplerian rotation and that the orbit is circular and perpendicular to the plane of the sky, the velocity difference yields a combined binary mass of $\sim 1.1 M_\odot$. Assuming a mass ratio of $\sim 13 (M_B/M_{\text{VLA}3})$, the derived masses of sources B and VLA3 are 1.0 and 0.08 $M_\odot$, respectively. The estimated dynamical mass of source B is consistent with the total gas mass derived from the 1.4 mm dust continuum image (1.05 $M_\odot$). This in turn supports our assumption above that both sources B and VLA 3 are forming a bound binary system. Hereafter we refer to this binary protostar as the SVS 13 B/VLA 3 protobinary system. We also note that source A, which is much closer to VLA 3 in the 3 mm dust continuum image, is probably farther away in foreground or background. This shows that 2D images can be very misleading unless additional kinematic information like that derived from our $N_2H^+$ observations is also considered.

### 4.4. Hierarchical Fragmentation in SVS 13: Initial Fragmentation Versus Rotational Fragmentation

The 3 mm dust continuum image shows three distinct cores (A, B, and C) in SVS 13, which are roughly aligned along a line in the northeast–southwest direction (see Figure 1). The morphology of the $N_2H^+$ emission approximately follows this alignment. Nevertheless, there is an emission gap (hole) between the $N_2H^+$ main core and the small clumps toward northeast of source A (see Figure 2). This gap is possibly caused by an effect of the outflow, which releases great amounts of CO molecules and thus destroys $N_2H^+$ around source A (see Aikawa et al. 2001 and also discussion in Paper II). The projected separations between sources A–B and B–C are $\sim 5000 \text{ AU}$ and $\sim 7000 \text{ AU}$, respectively. Previous single-dish sub-mm and mm maps show a large-scale common envelope with a radius of $\sim 20000 \text{ AU}$ (0.1 pc), surrounding these three cores and elongated in the same direction (Chini et al. 1997; Chandler & Richer 2000). Based on these associated morphologies, we speculate that the three cores (A, B, and C) were formed by initial fragmentation$^8$ of a large-scale filamentary prestellar core.

On the other hand, in the SVS 13 B subcore, a binary protostar with a projected separation of 3800 AU is forming. The velocity field associated with this binary protostar is dominated by rotation and the ratio of rotational energy to gravitational energy is estimated to be $\beta_{\text{rot}} \sim 0.025$. The $\beta_{\text{rot}}$ value is believed to play an important role in the fragmentation process (see reviews by Bodenheimer et al. 2000 and Tohline 2002). Considering that magnetic fields support fragmentation, Boss (1999) has shown that rotating cloud cores fragment when $\beta_{\text{rot}} > 0.01$ initially (but see also Machida et al. 2005). Based on this velocity structure, we suggest that the binary protostar in SVS 13 B is formed through rotational fragmentation of a single collapsing prestellar core.

Altogether we suggest a hierarchical fragmentation picture for SVS 13. (1) A large-scale filamentary prestellar core was initially fragmented into three subcores (sources A, B, and C) due to turbulence (see the review by Goodwin et al. 2007). (2) These subcores are continually contracting toward higher degrees of central condensation, and the rotation of the subcores is getting faster and dominates the gas motion instead of turbulence. (3) At a certain point, the condensations inside these subcores become gravitationally unstable and start to collapse separately to form either a binary protostar (e.g., SVS 13 A and B) if the rotational energy is larger than a certain level (e.g., $\beta_{\text{rot}} > 0.01$) or a single protostar (e.g., SVS 13 C?) if the rotational energy is not high enough to trigger the fragmentation.

### 4.5. Accretion onto Protobinary: Simulations Versus Observations

Accretion onto a protobinary is one of the most important contributions to the final parameters of the system. Numerical simulations of accretion have found that the main dependencies are on the binary mass ratio and the relative specific angular momentum, $j_{\text{inf}}$, of the infalling material (see Bate & Bonnell 1997 and Bate 2000). For unequal mass components, low $j_{\text{inf}}$ material is accreted by the primary or its disk; for higher $j_{\text{inf}}$, the infalling material can also be accreted by the secondary or its disk; when $j_{\text{inf}}$ approaches the specific angular momentum of the binary system $j_\text{bin}$, circumbinary disk formation begins; when $j_{\text{inf}} \gg j_\text{bin}$, the infalling material is accreted by neither component but only forms a circumbinary disk.

In our observations conducted at OVRO, ATCA, and PdBI, we find in several protobinary systems that only one component is associated with a great amounts of circumstellar dust while the other is somewhat naked, e.g., SVS 13 B/VLA 3 (this work), CB 230 (Launhardt 2001; R. Launhardt et al. 2009, in

$^8$ The term “initial fragmentation” refers to turbulent fragmentation in large-scale cores, prior to the protostellar phase. This leads to the formation of individual subcores, which are usually not gravitationally bound to each other.
preparation), and BHR 71 (Paper II). A similar situation was also found in the SVS 13 A protobinary system (Anglada et al. 2004). In fact, there is a trend derived from observations of only a very small number of sources (i.e., not a statistically significant sample) that unequal circumstellar masses (mass ratios below 0.5) protobinary systems are much more common than those equal masses systems (Launhardt 2004; X. Chen et al. 2009, in preparation). Since the detection bias goes toward equal-mass protobinary systems (e.g., sources VLA 1623, LMW2000, and L723 VLA2, Launhardt 2004), we consider this trend is not negligible. The large contrast between the two components implies that the accretion and hence development of a circumstellar disk occurs preferentially in only one component, with the disk absent or much less significant in the other one.

According to the definition in Bate & Bonnell (1997, hereafter BB97), we can calculate the specific orbital angular momenta of binary system as $j_b = \sqrt{GM_bD}$ (where $G$, $M_b$, and $D$ are the gravitational constant, total binary mass, and separation, respectively), and consider it as an unity. Taking SVS 13 B as an example, we assume $M_B = 1.0 M_\odot$ (see Section 4.3) and $D = 3800$ AU, and adopt the specific angular momentum derived from the N$_2$H$^+$ velocity field as $j_{\text{inf}} \sim 1.5 \times 10^{16}$ m$^2$ s$^{-1}$. We then derive $j_{\text{inf}}/j_b \sim 0.1$. This ratio is exactly corresponding to the simulated case that only circumprimary disk could be formed in an accreting protobinary system (see BB97). Therefore, the fact that only one component in a protobinary system is associated with a large amount of circumstellar material (or a circumstellar disk) could be explained by the relatively low specific angular momentum in the infalling envelope.

For a comparison, we list in Table 6 the corresponding parameters of L1551 IRS5, a well-studied protobinary system which we already knew the information of infalling gas and binary parameters (e.g., dynamical mass and separation). In contrast to SVS 13B, L1551 IRS5 apparently corresponds to a case of accretion of material with relatively higher angular momentum ($j_{\text{inf}}/j_b \sim 1.0$), and both components in the system are observed with a circumstellar disk (see Rodríguez et al. 1998), which is also consistent with the theoretical simulation in BB97. Nevertheless, so far the data which would reveal the link between specific angular momenta and formation of circumstellar disks are very rare, and no statistically significant correlations can be derived yet.

5. CONCLUSION

We present IRAM-PdBI observations in the N$_2$H$^+$(1 – 0) line and the 1.4 and 3 mm dust continuum toward the low-mass protostellar core SVS 13. Complementary infrared data from the Spitzer Space Telescope are also used in this work. The main results are summarized below:

1. The 3 mm dust continuum image resolves four sources in SVS 13, named A, B, C, and VLA 3, respectively. Source C lies outside of the view at 1.4 mm, while source VLA 3 is not seen in the 1.4 mm continuum image. The separations between sources A–B and B–C are measured to be $\sim 5000$ AU and $\sim 7000$ AU, respectively. Assuming optically thin dust emission, we derive total gas masses of $\sim 0.2 - 1.1 M_\odot$ for the sources.

2. N$_2$H$^+$ (1–0) emission is detected in SVS 13. The emission is spatially associated with the dust continuum sources B and VLA 3. The excitation temperature of the N$_2$H$^+$ line is $\sim 11$ K. The FWHM radius of the N$_2$H$^+$ core is $\sim 1520$ AU. The line widths are roughly constant within the interiors of the core and large line widths only occur in the gap between the two dust continuum sources and a jet-like extension at the edge of the core. The observed mean line width is $\sim 0.48$ km s$^{-1}$ and the derived virial mass of the N$_2$H$^+$ core is $\sim 0.7 M_\odot$.

3. We derive the N$_2$H$^+$ radial velocity field for SVS 13. The velocity field shows a systematic velocity gradient of $\sim 28$ km s$^{-1}$ pc$^{-1}$ across the dust continuum sources B and VLA 3, which could be explained by rotation. We estimate the specific angular momentum of $\sim 0.47 \times 10^{16}$ m$^2$ s$^{-1}$ pc ($\sim 1.45 \times 10^{16}$ m$^2$ s$^{-1}$) for this N$_2$H$^+$ core. The ratio of rotational energy to gravitational energy is $\sim 0.025$.

4. Infrared emission from sources A and C is detected at Spitzer IRAC bands and MIPS bands. Source A is driving a chain of HH objects, as seen in the IRAC 4.5 µm infrared image. No infrared emission is detected from source B in any Spitzer bands, suggesting the source is deeply embedded.

5. By fitting the spectral energy distributions, we derive the dust temperature, bolometric temperature, and bolometric luminosity for the sources A, B, and C. We find that sources B and C are Class 0 protostars, while source A could be a Class I/I1 transition object.

6. The velocity field associated with sources B and VLA 3 suggests that the two sources are forming a physically bound protobinary system embedded in a common N$_2$H$^+$ core. The estimated dynamical mass of source B ($\sim 1.0 M_\odot$) is consistent with its gas mass derived from the mm dust continuum images.

7. Based on the morphologies and velocity structures, we suggest a hierarchical fragmentation picture for SVS 13: the three sources (A, B, and C) in SVS 13 were formed by initial fragmentation of a filamentary prestellar core, while the protobinary systems SVS 13 B/VLA 3 and SVS 13 A were formed by rotational fragmentation of the collapsing subcores.

8. Our observations conducted at OVRO, ATCA, and PdBI find in several protobinary systems that only one component is associated with a large amount of circumstellar material, while the other is somewhat naked, implying that the accretion and hence development of a circumstellar disk occurs preferentially in only one component, with the disk absent or much less significant in the other one. We find that this situation could be explained by the relatively low specific angular momentum in the infalling envelope, which is supported by both simulations and observations.

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### Table 6

| Source       | Class | $j_{\text{inf}}$ (m$^2$ s$^{-1}$) | $M_\odot$ (M$_\odot$) | Sepa. (AU) | $j_B$ (m$^2$ s$^{-1}$) | $j_{\text{inf}}/j_B$ | Refs. |
|--------------|-------|----------------------------------|------------------------|------------|-----------------------|----------------------|-------|
| L1551 IRS5   | 1     | $3.1 \times 10^{16}$             | 1.2 (0.4)              | 300        | $3.0 \times 10^{16}$  | $\sim 1.0$           | 1, 2   |
| SVS 13 B     | 0     | $1.5 \times 10^{16}$             | 1.1 (<0.1)             | 2800       | $2.7 \times 10^{17}$  | $\sim 0.1$           | 3      |

**Notes.**

a Specific angular momenta of infalling envelopes. For source L1551 IRS5, the rotation radius and velocity are estimated to be 900 AU and 0.23 km s$^{-1}$, respectively (see Saito et al. 1996).

b Total mass of the binary systems. The mass of L1551 IRS5 is dynamical mass estimated from orbital motion (see Rodríguez 2004).

c References: (1) Saito et al. (1996); (2) Rodríguez (2004); (3) This work.
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