The fate of massive cold clumps, their internal structure, and collapse need to be characterized to understand the initial conditions for the formation of high-mass stars, stellar systems, and the origin of associations and clusters. We explore the onset of star formation in the 75 $M_\odot$ SMM1 clump in the region ISOSS J18364−0221 using infrared and (sub-)millimeter observations including interferometry. This contracting clump has fragmented into two compact cores SMM1 North and South of 0.05 pc radius, having masses of 15 and 10 $M_\odot$, and luminosities of 20 $L_\odot$ and 180 $L_\odot$. SMM1 South harbors a source traced at 24 and 70 $\mu$m, drives an energetic molecular outflow, and appears supersonically turbulent at the core center. SMM1 North has no infrared counterparts and shows lower levels of turbulence, but also drives an outflow. Both outflows appear collimated, and parsec-scale near-infrared features probably trace the outflow-powering jets. We derived mass outflow rates of at least $4 \times 10^{-3}$ $M_\odot$ yr$^{-1}$ and outflow timescales of less than $10^4$ yr. Our HCN(1−0) modeling for SMM1 South yielded an infall velocity of 0.14 km s$^{-1}$ and an estimated mass infall rate of $3 \times 10^{-5}$ $M_\odot$ yr$^{-1}$. Both cores may harbor seeds of intermediate- or high-mass stars. We compare the derived core properties with recent simulations of massive core collapse. They are consistent with the very early stages dominated by accretion luminosity.

Key words: dust, extinction – ISM: clouds – ISM: individual (ISOSS J18364−0221) – ISM: jets and outflows – ISM: kinematics and dynamics – stars: formation

Online-only material: color figures

1. INTRODUCTION

1.1. Star Formation in Massive Cold Clumps

The early phases of star formation occur in the densest and coldest regions within molecular clouds, i.e., dense cold cores. Detailed studies of nearby star-forming molecular clouds have led to a conception of the evolution of individual low-mass stars from prestellar cores to pre-main-sequence stars (e.g., Andrê & Montmerle 1994; di Francesco et al. 2007; Ward-Thompson et al. 2007). The formation of high-mass stars ($M \gtrsim 10 M_\odot$) is less understood, in particular its earliest stages and the link to the origin of associations and clusters (Zinnecker & Yorke 2005, and references therein). The fate of massive cold clumps, their internal structure, and collapse need to be characterized to understand the initial conditions for the formation of high-mass stars, stellar systems, and the origin of associations and clusters. The early phases of star formation occur in the densest and coldest regions within molecular clouds, i.e., dense cold cores. Detailed studies of nearby star-forming molecular clouds have led to a conception of the evolution of individual low-mass stars from prestellar cores to pre-main-sequence stars (e.g., Andrê & Montmerle 1994; di Francesco et al. 2007; Ward-Thompson et al. 2007). The formation of high-mass stars ($M \gtrsim 10 M_\odot$) is less understood, in particular its earliest stages and the link to the origin of associations and clusters (Zinnecker & Yorke 2005, and references therein). The fate of massive cold clumps, their internal structure, and collapse need to be characterized to understand the initial conditions for the formation of high-mass stars, stellar systems, and the origin of associations and clusters. The clump is located in the region ISOSS J18364−0221 that has been identified using the IRAS Survey (ISOSS; Lemke et al. 1996; Stickel et al. 2007) at 170 $\mu$m to establish far-infrared color temperatures. Krause (2003) and Krause et al. (2004) selected sources containing a large fraction of cold dust, and subsequent studies revealed a population of cold clumps (Krause et al. 2003; Hennemann et al. 2008) and a collapsing massive core (Birkmann et al. 2007).
Derived from the near-infrared extinction over a 15′ × 15′ field (~100 pc²), the cloud complex associated with the star-forming region comprises a mass $M \approx 3200 \, M_\odot$. In the same manner, a lower-mass limit $M \geq 460 \, M_\odot$ was found for the central region (~1 pc²), while the far-infrared and submillimeter measurements give a luminosity $L \approx 800 \, L_\odot$, an average dust temperature of about 15 K and a mass of $900^{+450}_{-330} \, M_\odot$. This region contains two clumps detected in the submillimeter continuum named SMM1 and SMM2 that are separated by about 1/5 along the east–west direction. The SMM1 clump is subject of this publication. Its effective radius is about 0.2 pc, and from the thermal emission a characteristic dust temperature of 16–18 K and a mass of $800 \, M_\odot$ was found. The molecular line observations reported in Birkmann et al. (2006) show redshifted self-absorption that is interpreted as signature of collapse motions. Furthermore, at least one outflow is present. The outflow properties resulting from the single-dish observations, i.e., the outflow mass of about 18 $M_\odot$, and the mass outflow rate of $10^{-7} \, M_\odot$ yr⁻¹, are comparable to values derived for outflows from presumed high-mass star precursors. These results render the SMM1 clump a promising object to study the early phases of collapse and fragmentation occurring in massive cold cores.

The detailed study of this source we present here made use of recently collected infrared and (sub-)millimeter data described in the next section. They reveal two star-forming cores and molecular outflows (Section 3). In Section 4, we discuss the core properties in the context of early-stage star formation and present a comparison of the observed HCN spectra with simple radiative transfer models. Finally, the results are summarized in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Near-Infrared Observations

Imaging observations in the J, H, and Ks band toward ISOSS J18364−0221 have been obtained and are described in Birkmann et al. (2006). Additional near-infrared images in the H$_2$ ν = 1−0 (S(1) line ($\lambda = 2.122 \, \mu$m)) were taken with the Calar Alto 3.5 m telescope in 2005 October using the prime-focus wide-field camera Omega-2000 (Baumeister et al. 2003). Omega-2000 features a field of view (FOV) of $15.4 \times 15.4$ arcmin² with a pixel scale of 0′′.496 per pixel⁻¹. The exposures were dithered on source to allow for sky subtraction. The data reduction was done using IRAF.

2.2. Mid- and Far-Infrared Observations

IRAC (Fazio et al. 2004) imaging in all four photometric bands, MIPS (Rieke et al. 2004) imaging at 24 μm and 70 μm, and MIPS SED mode observations were undertaken with Spitzer (Werner et al. 2004). The basic flux calibrated imaging data of the Spitzer Science Center (SSC) pipeline were used for further data reduction and analysis. Cosmetic corrections and astrometric refinement were performed with MOPEX software (Makovoz & Marleau 2005), and the final images were combined using scripts in IRAF. Aperture photometry and point-spread function (PSF) fitting was done with the aperture corrections given in the IRAC data handbook and on the SSC Web site.² The MIPS SED mode calibration is based on a spectrum of α Boo (Low et al. 2005) and the measured MIPS 70 μm fluxes. The calibration uncertainties are about 2% (IRAC; Reach et al. 2005), 4% (MIPS 24; Engelbracht et al. 2007), and 10% (MIPS 70; Gordon et al. 2007). The resulting photometric accuracy is estimated to 5% (IRAC), 10% (MIPS 24), and 20% (MIPS 70 and SED).

2.3. Submillimeter Observations

The submillimeter continuum observations with SCUBA at the James-Clerk-Maxwell Telescope (JCMT) are outlined in Birkmann et al. (2006). In light of the results from the interferometric observations that are described in the next section, we re-analyzed the jiggle maps. The ORAC-DR (Jenness & Economou 1999) and SURF (Jenness & Lightfoot 1998) software were used for data reduction and the photometric calibration based on maps of Uranus acquired shortly before and after the observations. Further analysis as described in Sandell & Weintraub (2001) used the MIRIAD software (Sault et al. 1995). The deviations of the JCMT beam from a Gaussian have been considered by using the Uranus maps to construct symmetric beam models and deconvolve the maps of the target regions. The derived beam sizes are 8′′ at 450 μm and 14′′ at 850 μm. The maps were restored with Gaussian beams of 8′′ and 14′′, respectively, and fluxes as well as deconvolved source sizes have been derived by fitting Gaussian components. The noise levels (1σ) in the restored maps are 100 mJy beam⁻¹ at 450 μm and 23 mJy beam⁻¹ at 850 μm. The photometric accuracy obtained is estimated to 30% at 450 μm and 20% at 850 μm. For a large aperture covering the SMM1 clump, the photometric results reproduce those of Birkmann et al. (2006) within the uncertainty ranges.

2.4. Millimeter Observations

We have carried out millimeter observations using the IRAM 30 m and Plateau de Bure Interferometer (PdBI). The molecular lines CO(2-1), HCO⁺(1–0), and HCN(1–0) have been observed together with the continuum at 1.3 mm and 3.4 mm. The line frequencies are 230.538 GHz for CO(2-1) and 89.18852 GHz for HCO⁺(1–0). The HCN(1–0) transition includes three hyperfine components within 4 MHz at 88.630416 GHz (F1→1), 88.631847 GHz (F2→1), and 88.633936 GHz (F0→1).3 The PdBI configurations C and D were utilized; D was observed in 2006 September and C in 2007 April with the new generation facility receivers. Spectral resolutions of 40 kHz (3 mm lines), 160 kHz (CO(2-1)), 1.25 MHz (3.4 mm continuum, 3×160 MHz bandwidth), and 2.5 MHz (1.3 mm continuum, 2×320 MHz bandwidth) were used. Phase calibrators were 1749-096 and 1741-038, additional amplitude calibrators were MWC349 and 3C273. Corresponding short-spacing observations were accomplished in 2007 February at the IRAM 30 m as on-the-fly maps using the single-pixel heterodyne receivers with the VESPA correlator and spectral resolutions of 80 kHz (1 mm lines, 80 MHz bandwidth) and 20 kHz (3 mm lines, 40 MHz bandwidth). The data were reduced and calibrated with the GILDAS4 software. GILDAS was also used to combine the short-spacing and interferometric data for the lines. In the case of CO, we chose to convert the measured visibilities to maps using a weighting scheme that achieves the highest spatial resolution (a synthesized beam size of 1″85 × 1″33) at the expense of sensitivity for extended emission. Therefore, the combined CO map does not recover the complete flux. Compared to the single-dish spectra, the line...

² NIST Recommended Rest Frequencies for Observed Interstellar Molecular Microwave Transitions: http://physics.nist.gov/restfreq.
³ http://www.iram.fr/IRAMFR/GILDAS
For HCN, the comparison of the extracted spectra shows that the flux measured in the single-dish data is reproduced in the combined map. The synthesized continuum beam sizes are 1.9' × 1.0' (P.A. 11.6°) at 1.3 mm and 4.6' × 3.2' (P.A. 6.1°) at 3.4 mm. We reach noise levels (1σ) in the cleaned maps of 0.6 mJy beam⁻¹ (1.3 mm continuum), 0.13 mJy beam⁻¹ (3.4 mm continuum), 0.5 Jy beam⁻¹ km s⁻¹ (CO(2-1)), 0.07 Jy beam⁻¹ km s⁻¹ (HCO⁺(1-0)), and 0.1 Jy beam⁻¹ km s⁻¹ (HCN(1-0)). Assuming a dust temperature of 20 K, we are sensitive to total masses of about 0.2 $M_\odot$ (3σ in the 1.3 mm continuum). The noise level (1σ) in the individual HCN(1–0) spectra used for the modeling is 0.1 K. The 1.2 mm continuum was observed with the MAMBO-2 bolometer array in 2007 March. The MOPSIC software was used for data reduction and the noise level (1σ) in the resulting map is 10 mJy beam⁻¹. The photometric accuracy is estimated to 20%.

3. RESULTS

3.1. Multiwavelength Maps of SMM1

In Figures 1 and 2, we show multiwavelength maps observed toward ISOSS J18364−0221 SMM1. In the interferometric millimeter continuum observations, SMM1 is resolved into two...
Figure 2. ISOSS J18364−0221 SMM1 CO(2–1) and HCO+(1–0) observations. Top row: observations at 1.3 mm; continuum emission is shown in gray scale, and CO(2–1) line emission in dashed red (velocity range 20–30 km s\(^{-1}\); contours at 2, 3, ..., 7 Jy beam\(^{-1}\) km s\(^{-1}\)) and solid blue (velocity range 40–50 km s\(^{-1}\); contours at 3, 4, ..., 9 Jy beam\(^{-1}\) km s\(^{-1}\)). Besides, the beam pattern in steps of 20% and the integrated CO(2–1) spectrum are plotted. Bottom row: observations at 3.4 mm; continuum emission is shown in gray scale, and HCO+(1–0) line emission in dashed red (velocity range 20–30 km s\(^{-1}\); contours at 60, 80, ..., 200 mJy beam\(^{-1}\) km s\(^{-1}\)) and solid blue (velocity range 40–50 km s\(^{-1}\); contours at 100, 120, ..., 400 mJy beam\(^{-1}\) km s\(^{-1}\)). Besides, the beam pattern in steps of 10% and the integrated HCO+(1–0) spectrum are plotted.

(A color version of this figure is available in the online journal.)

cores SMM1 North and SMM1 South (Figure 1, lower panels), separated by 9′′5 (ca. 21000 AU). In the near-infrared (Figure 1, upper left), noticeable extinction and reddening is present in the surrounding of SMM1. There are no near-infrared sources detected toward the (sub-)millimeter peaks. The mid-infrared measured with IRAC (Figure 1, upper right) is dominated by extended emission in the 8 μm band along the outer rim of SMM1. Toward the center of SMM1, a filamentary structure is observed in absorption, and no stellar objects are associated. At 24 μm (Figure 1, lower left), a point source at SMM1 South shows up. At this wavelength, the extended emission around SMM1 is also visible, and in the northwest a dip remains, but the absorption feature is superposed by the PSF of the southern source. No obvious 24 μm source toward SMM1 North is detected. Similarly, SMM1 South emits at 70 μm (Figure 1, lower right). The wide PSF overlays possible extended emission at the rim of SMM1, and no obvious emission at SMM1 North is detected.

In the interferometric 1.3 mm continuum map (Figure 2, top row), both SMM1 North and South appear slightly extended to the north, but the beam sidelobes may affect the morphology. At 3.4 mm they appear unresolved (Figure 2, bottom row), and none of the extensions are traced. The contours in Figure 2 derived from the emission in the line wings of the CO(2–1) and HCO+(1–0) transitions reveal two molecular outflows. SMM1 South constitutes the origin of a northeast-to-southwest (P.A. ca. 50°) outflow that also gives rise to the mid-infrared features. Toward SMM1 North, an outflow in east-to-west direction (P.A. ca. −80°) is found. Its red lobe blends into the red lobe of the SMM1 South outflow. Most prominent in CO(2–1) is the SMM1 North blue outflow lobe that appears collimated. In HCO+(1–0), the blue lobe of the SMM1 North outflow is strongest and it also shows a rather low outflow opening angle, but in both cases the outflows are traced only close to the cores and we could not derive an accurate quantitative measure.

In Figure 3, we show the near-infrared H\(_2\) ν = 1−0 S(1) (λ = 2.122 μm) line emission map. This map has been derived by subtracting the scaled K-band image from the narrowband image so that stars canceled out. Stars that were not properly subtracted have been masked afterward for clarity. As shown in the inset of Figure 3, toward the blue and red lobes of the molecular outflow driven by SMM1 South there is patchy near-infrared H\(_2\) emission. Such features trace protostellar jets, and the emission probably arises from collisionally excited H\(_2\) in shocked gas (Elias 1980; Reipurth & Bally 2001, and references therein). This is supported by faint filamentary emission in the 4.5 and 5.8 μm bands we detected lateral to SMM1 South along northeast-to-southwest and in the vicinity of SMM1 North (yellowish features in Figure 1, top right). These bands contain several H\(_2\) lines (Noriega-Crespo et al. 2004; Smith & Rosen...
Only a weak near-infrared feature is detected close to the blue lobe of the SMM1 North outflow. On the large-scale map, we found additional filaments of H$_2$ emission. Though they are not exactly aligned with the molecular outflows, they can be assigned to individual lobes which would make it necessary that the proposed jets show bending resulting in S-shapes. The outermost features in the northeast and southwest are located at a projected distance of about 6.7 pc from each other, and the southwest feature is at a projected distance of about 4.6 pc from SMM1 South. Among the sources detected in the vicinity of the features, we do not find other candidates for jet-driving young stellar objects.

### 3.2. SEDs and Core Sizes

In the near-infrared and at 3.6 μm no emission is coinciding with SMM1 North or South and we derived upper flux limits from our maps. Close to SMM1 North, the emission in the 4.5 and 5.8 μm IRAC bands were measured on levels of 71 and 155 μJy. In the 4.5 μm band there is extended emission overlapping with the SMM1 South position, where the flux is about 1.2 mJy. At 8 μm no counterparts corresponding to SMM1 North or South are detected.

The source toward SMM1 South clearly dominates the emission at 24 and 70 μm. Due to the separation of about 9′ between SMM1 North and South, the derivation of fluxes at these wavelengths is impaired toward SMM1 North (PSF FWHM of about 6′ and 17′). We accomplished PSF subtraction to remove the emission of SMM1 South. At both 24 and 70 μm, the residual maps do not reveal a second compact source at SMM1 North. The 3σ upper limits for SMM1 North were derived from the residual scatter at its position. We ended up with 24 μm fluxes of 199 mJy and 15.7 Jy for SMM1 South and upper flux limits of 5.3 mJy and 177 mJy for SMM1 North at 24 and 70 μm, respectively.

To derive submillimeter fluxes for the two internal SMM1 components, we fitted a Gaussian to each peak on the 450 μm map and an extended Gaussian to account for the surrounding clump emission. The same sizes convolved with the 14″ Gaussian were then used as fixed parameters to extract 850 μm fluxes. The clump background is well fitted with a deconvolved FWHM size of 68″ and total fluxes of 12.3 Jy (450 μm) and 2.02 Jy (850 μm). For SMM1 South we got a deconvolved...
Table 1  
Continuum Flux Measurements and Derived Core Properties

| Parameter                  | SMM1 North | SMM1 South |
|----------------------------|------------|------------|
| 24 μm flux (mJy)           | <5.3       | 199        |
| 70 μm flux (mJy)           | <177       | 157000     |
| 450 μm flux (mJy)          | 2660       | 4420       |
| 850 μm flux (mJy)          | 476        | 622        |
| 30 m 1.2 mm flux (mJy)     | 156        | 151        |
| PdBI 1.3 mm flux (mJy)     | 49         | 80         |
| PdBI 3.4 mm flux (mJy)     | 3.9        | 4.1        |
| FWHM size (AU)             | 14000 × 7000 (P.A. 34°) 10000 × 8000 (P.A. −50°) |
| Luminosity ($L_\odot$)     | 20         | 180        |
| Dust temperature * (K)     | 15         | 22         |
| $\nu_{\text{peak}}$ (cm$^{-2}$) | $2.7 \times 10^{23}$ | $2.4 \times 10^{23}$ |
| Mass c ($M_\odot$)         | 15         | 10         |
| $\langle n_H \rangle$ (cm$^{-3}$) | $5 \times 10^5$ | $4 \times 10^5$ |

Notes.

* Derived from the single-dish continuum flux measurements/upper limits between 70 and 1200 μm.

* Derived from the interferometric 1.3 mm continuum map and the given dust temperatures.

* Derived from the interferometric 3.4 mm continuum map and the given dust temperatures.

FWHM size of 5.9″ and fluxes of 4.42 Jy (450 μm) and 662 mJy (850 μm), and for SMM1 North a size of 7″0 and fluxes of 2.66 Jy (450 μm) and 476 mJy (850 μm). The total fluxes we derived are higher than those given in Birkmann et al. (2006) because we allowed for a larger extent of the background component. As in the 850 μm map (Figure 1), SMM1 North and South blend into a single-elongated maximum in the single-dish 1.2 mm map. Therefore, we extracted fluxes in the same way for both sources, using the positions from the submillimeter and allowing for a pointing offset. The derived fluxes are 151 mJy for SMM1 South and 156 mJy for SMM1 North.

The continuum fluxes for both cores are listed in Table 1. Figure 4 shows the SEDs of the continuum emission toward the two sources including the jet features in the IRAC bands. The curves fitted to the data are described in the next subsection.

From the interferometric continuum maps we also derived fluxes for both sources by fitting Gaussian components. In the case of SMM1 South, 80 mJy (1.3 mm) and 4.1 mJy (3.4 mm) and FWHM dimensions of 4″.4 × 3″.6 (P.A. −50°) were measured, corresponding to a core size of ~9000 AU. For SMM1 North, the fluxes are 49 mJy (1.3 mm) and 3.9 mJy (3.4 mm) and FWHM sizes of 6″.3 × 3″.1 (P.A. 34°) were measured, corresponding to a more elliptical core of 14,000 × 7000 AU.

We also estimated the bolometric luminosities from the two SEDs. SMM1 South has a luminosity $L \approx 180 L_\odot$, and for SMM1 North we got $L \approx 20 L_\odot$ using the upper limit fluxes in the infrared.

3.3. Dust Temperatures and Masses

Ossenkopf & Henning (1994) have derived dust opacities for dense protostellar cores, and for our analysis we used the model with thin ice mantles and coagulation at a gas density of $n_H = 10^9$ cm$^{-3}$ (OH5, $k_{1.3, \text{mm}} = 0.9$ cm$^2$ g$^{-1}$). To estimate the temperature uncertainties we also applied the model without ice mantles (OH2) and the initial, noncoagulated opacities (OH1). In Figure 4, we show the OH5 fit to the emission of SMM1 South using two modified Planck components assuming optically thin emission. The long-wavelength SED is matched by thermal dust emission at 22+4 K (solid line). From the fit we derived a dust mass of $M^\text{cold}_d = 0.12 M_\odot$. The fluxes at shorter wavelengths are reproduced by a dust component at 48 K with a dust mass of $M^\text{warm}_d = 5 \times 10^{-2} M_\odot$ (dashed line). For the SMM1 North source, we used the upper flux limit at 70 μm to derive an upper limit dust temperature of 15+9 K from a single component fit also shown in Figure 4. The corresponding dust mass is $M_d = 0.18 M_\odot$. Assuming a canonical gas-to-dust mass ratio of 100, the masses of the cores are ca. 12 $M_\odot$ (SMM1 South) and 18 $M_\odot$ (SMM1 North), with an uncertainty of about a factor of 2 (see Section 4.2).

Preserving the dust temperatures and masses, the expected continuum fluxes at 3.4 mm are 4.9 mJy (SMM1 South) and 4.8 mJy (SMM1 North), thus the measured fluxes trace about 10 $M_\odot$ for SMM1 South and about 15 $M_\odot$ for SMM1 North as compact components. The differences stem from the filtering in the interferometric observations. Using these masses and the core FWHM sizes of 9000 AU and 10,000 AU, we calculated volume-averaged densities ($n_H') = 3 M/(4\pi FWHM^3)$ which are $4 \times 10^5$ cm$^{-3}$ for SMM1 South and $5 \times 10^5$ cm$^{-3}$ for SMM1 North. The remaining mass of the SMM1 clump is located in a more extended envelope. From the dust temperatures and peak fluxes in the interferometric 1.3 mm continuum map, we derived peak column densities of $2.7 \times 10^{23}$ cm$^{-2}$ (SMM1 North) and $2.4 \times 10^{23}$ cm$^{-2}$ (SMM1 South). Table 1 summarizes the properties of the two detected cores.

3.4. Properties of the Molecular Outflows

From our CO (2–1) map we inferred the properties of the outflows. For this purpose it is necessary to convert the measured CO emission into molecular hydrogen column densities $N_{\text{HI}}$, and we used the relation $N_{\text{HI}} = 3 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s $\times \int T_{\text{mb}} dv$ from Osterloh et al. (1997).
The mass was then calculated as \( M = \mu m_{\text{H}_2} d^2 \sum N_{\text{H}_2} \Delta \Omega \), where \( \mu \) is the ratio of gas mass to hydrogen mass (taken to be 1.36), \( m_{\text{H}_2} \) is the mass of the hydrogen molecule, and \( \Delta \Omega \) is the solid angle covered by \( N_{\text{H}_2} \). The integrated emission in the CO map toward SMM1 traces 4.8 \( M_\odot \), compared to a mass of 75 \( \pm 30 \) \( M_\odot \) derived from the dust continuum emission (Birkmann et al. 2006). This discrepancy probably stems from the uncertainty of the above relation in combination with the missing flux in the CO map (see Section 2.4). Apparent also in the integrated CO(2–1) spectrum in Figure 2, the optical depth in the line is significant. Other outflow studies have found CO(2–1) optical depths on the order of 10 referring to a comparison with CO emission as described in Choi et al. (1993). In the case of SMM1 South, the fact that near-infrared \( \text{H}_2 \) emission is observed toward both molecular outflow lobes indicates that the difference in extinction is not very large. This suggests a high inclination \( i \) of the outflow axis with respect to the line of sight. Because we cannot further constrain the inclination, we assume \( i = 57.3^\circ \) for both outflows in the following, corresponding to the mean of a random distribution of outflow orientations. In Table 2, we list the parameters derived as described in Henning et al. (2000a) for the different outflow lobes, corresponding to line emission above 3\( \sigma \). Mean outflow velocities were derived from the mechanical momenta \( P \) and the masses using \( \langle v \rangle = P/M \), and halves of the lobe extents in outflow direction were taken as traveled distance to calculate the dynamical timescales. We interpret the given masses as lower limits, and as described in Section 2.4, the true masses are probably higher by roughly a factor of 5. The same applies to the mechanical momenta and the kinetic energies. While the mass derivation may be precise within factors of 2–4 (see Cabrit & Bertout 1990), the dynamical parameters are less certain and can be considered as order of magnitude estimates. Besides, the blending of the two red outflow lobes hampered our parameter derivation, so we regard the values derived for the blue lobes as more precise.

### 3.5. HCN Emission Toward SMM1

The three HCN(1–0) hyperfine components \( F_{1\rightarrow1}, F_{2\rightarrow1} \), and \( F_{0\rightarrow1} \) lie within 4 MHz and the expected line ratios are 3:5:1 in the optically thin case for local thermal equilibrium (LTE). The HCN(1–0) map integrated over all three components (Figure 5, left) shows a pronounced maximum toward SMM1 South, whereas only weak emission is detected at SMM1 North. It is possible that the minor peaks that are offset from SMM1 North stem from the molecular outflows, because it has been shown recently that HCN can be present there as well (Zhang et al. 2007). The HCN(1–0) spectra toward the center positions of SMM1 South and North are shown in the middle panels of Figure 5.

In the case of SMM1 North, the signal-to-noise ratio of HCN(1–0) is rather low (\( \approx 6 \)) and the line shapes are uncertain. As indicated in the plot, the positions of the peaks are consistent with a systemic velocity \( v_{\text{LSR}} = 36.1 \) km s\(^{-1}\). The observed line ratios (neglecting the noise) depart from the expected optically thin LTE ratios: \( F_{0\rightarrow1}/F_{2\rightarrow1} = 0.6 \) and \( F_{1\rightarrow1}/F_{2\rightarrow1} = 0.75 \) compared to 0.2 and 0.6 in the LTE case. Such hyperfine "anomalies" have also been observed toward star-forming clouds in the past (Walmsley et al. 1982). Gonzalez-Alfonso & Cernicharo (1993) have investigated this numerically and found that the velocity structure in the emitting cloud core could strongly affect the line ratios. In particular, they found that an increased \( F_{1\rightarrow1}/F_{2\rightarrow1} \) ratio indicates inward motion in the core. Line ratios similar to the SMM1 North spectrum were predicted for a subset of their models.

In the case of SMM1 South the HCN(1–0) spectrum is detected with a higher signal-to-noise ratio of up to 40. By fitting the line wings with a symmetric profile, we get \( v_{\text{LSR}} = 34.8 \) km s\(^{-1}\). The hyperfine components are characterized by complex line shapes and cannot be described within the optically thin LTE approximation. The main features of the line profiles are strong dips near the line centers. In essence, such dips can be interpreted: (1) as an artifact of the data combination, i.e., the short-spacing flux is not recovered when combining the interferometric and single-dish data; (2) as a physical effect, namely, as a result of the self-absorption of the internal radiation in the envelope. To illustrate that this is not an artifact of data reduction, we show the single-dish and interferometric HCN(1–0) spectra (integrated over 20\(^\prime\) \times 20\(^\prime\)) before their combination in the right panels of Figure 5. If the dips in the interferometric spectrum are a result of the missing short-spacing flux, then we should see prominent emission near the line centers in the single-dish data. However, both interferometric and single-dish spectra have strong dips that indicate that these line features are real.

### 4. DISCUSSION

#### 4.1. The Fragmentation and Column Density of the SMM1 Clump

Our observations reveal two major fragments toward the SMM1 clump. From its mean FWHM extent of 30,000 AU (Birkmann et al. 2006), we calculate a volume-averaged density of \( n_{\text{H}_2} = 9 \times 10^4 \) cm\(^{-3}\) for SMM1. The dust temperature of

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**Table 2**

| Outflow Parameter            | South Red Lobe | South Blue Lobe | North Red Lobe | North Blue Lobe |
|------------------------------|----------------|-----------------|----------------|-----------------|
| Projected velocities (km s\(^{-1}\)) | 40–50          | 20–30           | 40–50          | 20–30           |
| Solid angle (as\(^{2}\))       | 86             | 195             | 27             | 119             |
| Mass \(^{a}\) (\(M_\odot\)) | 0.066          | 0.15            | 0.023          | 0.12            |
| Mechanical momentum \(^{b}\) (\(M_\odot\) km s\(^{-1}\)) | 0.85           | -2.3            | 0.30           | -1.8            |
| Kinetic energy \(^{b}\) (J)    | \(1.7 \times 10^{38}\) | \(2.5 \times 10^{38}\) | \(1.8 \times 10^{38}\) | \(2.4 \times 10^{38}\) |
| Dynamical timescale \(^{b}\) (yr) | \(7.7 \times 10^{3}\) | \(7.0 \times 10^{3}\) | \(3.8 \times 10^{3}\) | \(5.8 \times 10^{3}\) |
| Mass outflow rate \(^{b}\) (\(M_\odot\) yr\(^{-1}\)) | \(8.6 \times 10^{-6}\) | \(2.1 \times 10^{-5}\) | \(6.0 \times 10^{-6}\) | \(2.1 \times 10^{-5}\) |
| Mechanical luminosity \(^{b}\) (\(L_\odot\)) | 1.8            | 2.9             | 3.9            | 3.4             |

**Notes.**

\(^{a}\) Masses are lower limits because of missing flux.

\(^{b}\) Assuming an inclination \( i = 57.3^\circ \) of the outflow axes.
16.5 K gives a Jeans length of about 17,000 AU and a Jeans mass of 0.7 \( M_\odot \) (Stahler & Palla 2005). This indicates that the two cores with masses more than 1 mag higher are not the direct result of thermal fragmentation, because one would then expect a number of cores with about one Jeans mass to form (e.g., Jappsen et al. 2005; Bonnell et al. 2006). The projected distance of the two cores is 21,000 AU. It is rather large compared to the radius of influence of radiative feedback from protostellar objects. The simulations of Krumholz et al. (2007) show that the latter is around 1000 AU in the first 20,000 yr of core collapse. This suggests that the two cores evolve individually in terms of radiative feedback, however a kinematic influence is not excluded. Krumholz & McKee (2008) proposed a lower column density threshold of 1 g cm\(^{-2}\) (\( N_{\text{th}} = 2 \times 10^{22} \text{ cm}^{-2}\)) for the formation of high-mass stars. For the SMM1 clump, we derived a peak column density of 7 \( \times 10^{22} \text{ cm}^{-2}\) from the single-dish 1.2 mm map peak flux. It does not reach the proposed limit. However, the core peak column densities lie beyond the threshold (see Table 1). This shows that observations with high spatial resolution are required to evaluate the core properties.

### 4.2. Properties of the Two Millimeter Cores

The two detected cores SMM1 North and South appear quite similar at long wavelengths because they are of nearly the same size and exhibit comparable continuum emission. However, the derived core masses depend crucially on the assigned dust temperatures, and these are determined by the flux levels in the far-infrared. At wavelengths below \( \sim 100 \mu\text{m} \), the SMM1 clump of about 75 \( M_\odot \) is expected to become optically thick for continuum emission, and our Planck component fit does not take this into account. We therefore neglect the fitted warm component for SMM1 South in the rest of the discussion. Also for the cold components, we may have underestimated the characteristic dust temperature. However, because of its mass the far-infrared continuum optical depth of SMM1 is expected to be of the order of unity only. This means that a significantly higher dust temperature, corresponding to a lower mass and in consequence to a lower optical depth, would not be consistent with the far-infrared fluxes. Thus, the resulting uncertainty of the masses are about a factor of 2, but the general averaging along the line of sight could introduce larger errors. Furthermore, our mass derivation relies on the used dust opacities. While our choice of the OH5 model is rather conservative and the results can be compared to other studies, the true opacities may well differ. In the following, we take the derived masses at face value.

Both SMM1 North and South are compact and appear to drive individual outflows. Therefore, we suspect them to form individual stars or stellar systems of a few. With about 10 and 15 \( M_\odot \), SMM1 South and North represent cores of intermediate mass. From the comparison of core and stellar mass distributions, there are tentative indications that the star-forming efficiency on the scales of individual cores is between 25% and 50% (see e.g., Krumholz 2008, and references therein).

Under this assumption, one would expect both cores to form intermediate-mass protostars or protostellar systems in case none of the surrounding matter enters in the core collapse. However, the latter is probable because of the large-scale collapse motions that have been observed toward SMM1. In comparison to samples of low-mass dense cores, SMM1 North and South are denser by a factor of 10 (see Motte et al. 2007). While their sample of four clumps were reported (Ward-Thompson et al. 1999), so both cores lie above. They rather resemble the objects found in IRDCs by Rathborne et al. (2007). While their sample of four clumps (we use a different nomenclature here) have masses of 100 \( M_\odot \) and greater, the small-scale cores are several thousand AU in size and their masses are 2–21 \( M_\odot \) with the exception of one hot molecular core candidate. As in the case of SMM1 South, 24 \( \mu\text{m} \).
sources are associated with those cores. Similar findings have been reported by Beuther & Steinacker (2007) for the more-massive core in IRDC 18223-3, in particular the remarkable low luminosity.

The SED of SMM1 South at wavelengths below about 80 \(\mu\)m (Figure 4) does not resemble the single thermal emission component reproducing the submillimeter and millimeter fluxes. A similar result was also derived in the study of a sample of 12 clumps detected in five other ISOSS star-forming regions (Hennemann et al. 2008) and for one core in the ISOSS J23053+5953 region (Birkmann et al. 2007). Warm and hot dust components are required to explain the emission down to 24 \(\mu\)m, and also emission from very small grains may contribute in this wavelength regime. The fact that SMM1 South appears as point source at 24 and 70 \(\mu\)m shows that this core contains a compact region of heated dust. Assuming half of the PSF FWHM (6\(''\) at 24 \(\mu\)m) as an upper limit, the emitting region has a size of less than 7000 AU. This is consistent with an embedded young stellar precursor that constitutes the driving source of the SMM1 South outflow.

SMM1 North lacks emission in the infrared. The only sign of star formation is the SMM1 North outflow, indicating that this core is also further evolved than a supposed prestellar stage. The characteristic dust temperature is constrained to an upper limit, and therefore in this case the derived core mass represents only a lower limit.

Regarding the motion of the two cores with respect to each other, their systemic velocities derived from the HCN spectra differ by about 1.3 km s\(^{-1}\) and SMM1 North appears to be receding. The estimated uncertainty is 0.5 km s\(^{-1}\). Nevertheless, the value is relatively high compared to the velocity dispersions of up to 0.5 km s\(^{-1}\) measured for the core-to-core motions, e.g., in NGC 1333 and Perseus (Walsh et al. 2007; Kirk et al. 2007). It corresponds to roughly 0.3 AU yr\(^{-1}\), and on a timescale of about 10\(^3\) yr the cores would cover their projected distance.

4.3. The Star-Forming Process Within the Cores

The SEDs of both cores are dominated by the emission at long wavelengths arising from cold dust. This emission does not disclose much information about the internal structure of the cores. The lack of mid-infrared emission and the low spatial resolution in the far-infrared, when compared to the expected scales of emitting regions, do also prevent clarification of the properties of the embedded source in the case of SMM1 South. SMM1 North is very likely less evolved, but we cannot exclude projection effects. More observations are needed to further constrain the star formation process in the detected cores. The core emission morphology in the far-infrared will be explored with the ESA Herschel mission. In the case of SMM1 South, high spatial resolution imaging beyond 20 \(\mu\)m combined with high sensitivity, possible with the MIRI instrument on James Webb Space Telescope (JWST), will severely constrain the properties of the embedded protostellar object. In the following, we discuss implications given by the derived outflow properties and our modeling of the HCN spectra.

4.3.1. Outflow Activity

Collimated outflows have been observed for low-mass cores and, more recently, also for young high-mass objects, supporting the disk accretion scenario (see Beuther & Shepherd 2005, and references therein). In the former case, a high degree of collimation is linked to early stages and a widening of the outflow opening angle follows during further evolution (Arce & Sargent 2006). According to some observational evidence, this holds for high-mass sources as well and may provide a basis for their evolutionary classification.

The fact that we observed rather collimated outflows close to their proposed origins SMM1 North and South is consistent with the idea that the embedded driving sources have formed and launched the outflows recently. This is supported by the estimated dynamical timescales of less than 10\(^4\) yr.

The outflow energetics change by orders of magnitude from low-mass cases to luminous high-mass driving sources (e.g., Wu et al. 2004; Henning et al. 2000b), and the span of outflow kinetic energies that have been derived is 10\(^{31}\) J \(\leq E_{\text{kin}} \leq 10^{41}\) J. For the sample of Beuther et al. (2002b) with \(L > 10^5\) L\(_\odot\), they got values on the order of \(E_{\text{kin}} \approx 10^{39}\) J. With \(E_{\text{kin}} \approx 5 \times 10^{38}\) J, the outflows of the SMM1 cores reach the same order of magnitude, in particular because the adopted masses are lower limits. They exceed those of low-mass cores.

So far we have only considered the molecular outflows close to the cores. The traced molecular gas has probably been entrained by collimated jets. If we assume that the H\(_2\) emission features at larger distances stem from these jets, which is supported by the rough alignment with the molecular outflows, we can derive a second timescale for the outflow activity of the cores. However, we cannot constrain the jet velocities from observations. Beuther et al. (2002b) used a ratio of jet velocity to molecular outflow velocity of 20, and for the SMM1 cores the resulting jet velocities are about 300 km s\(^{-1}\). This is in the range of velocities that have been observed for Herbig-Haro flows from low-luminosity sources (Reipurth & Bally 2001). From the measured offsets of the outermost H\(_2\) feature in the southwest we got a timescale of approximately 1.8 \times 10^3 yr for the SMM1 South jet. This is above the molecular outflow timescale of approximately 7 \times 10^3 yr. For the SMM1 North jet, the outermost feature in the west gives a timescale of about 7 \times 10^3 yr, which agrees with the molecular outflow timescale. Accounting for the overall uncertainties, these values are consistent with the proposed relation of jets and molecular flows, which of course does not exclude other scenarios.

Parsec-scale jets and outflows have been found toward many young low-mass stellar objects, mostly traced by optical or near-infrared line emission (Reipurth & Bally 2001). The more energetic outflows in the high-mass regime are therefore expected to also extend to these sizes, although few observations were reported to date (e.g., Bally 2008; Beuther et al. 2002a). The presumed jets from SMM1 support this idea. The filamentary and patchy structure observed in H\(_2\) can be caused by different factors. Besides the varying line-of-sight extinction, the local H\(_2\) abundance may play an important role in determining where the shock-excited emission arises, and the kinematics of internal shocks is presumably influenced by the penetrated medium. An interesting possibility is the connection to the mass ejection history of the driving source, which is linked to the accretion history for disk-driven outflows. The several features we detected indicate a varying mass-loss rate for the SMM1 cores. Such a burst mode of accretion may result from disk instability driven by infall (Vorobyov & Basu 2006).

The S-shape that we observe for the presumed SMM1 South jet can be interpreted as a precession of the outflow axis. The outermost feature we found in the southwest approximately lies on the projected outflow axis with P.A. \(\approx 50^\circ\) we derived from the molecular outflow lobes close to the core, while the features in between are offset to lower P.A. This means the core rotation axis is not along the line of sight, but rather has a high inclination.
4.3.2. Modeling of the HCN Emission

HCN appears to be more resistant to freeze-out in cold dense cores compared to CO-related molecules as HCO⁺ (Redman et al. 2008). Assuming that the HCN emission traces the dense gas in the core, we investigate in the following if the observed HCN(1–0) spectra can be, in principle, reproduced by simple models for the core. First, we considered the “one-layer” model where the core is spherically symmetric and homogeneous. We assumed that the observed spectrum is obtained toward the center of the core as the antenna beam size is little smaller than the spatial extent of the core. The parameters of the model are the hydrogen density \(n_{H_2}\), the temperature \(T_{\text{kin}}\), the molecular column density \(N_{\text{HCN}}\), the turbulent velocity \(v_{\text{turb}}\), and the regular velocity \(v_{\text{rad}}\) which characterizes the radial expansion or contraction of the core. Note that we do not specify the radius of the core as well as the actual abundance of HCN since the emergent spectrum for such a core depends on their product (see Pavlyuchenkov et al. 2008). Therefore, in the frame of this model we cannot independently constrain the relative HCN abundance, the radius of the core, or its mass.

Having specified the above parameters, we generated the model core and performed a line radiative transfer (LRT) simulation with the non-LTE code of Pavlyuchenkov & Shustov (2004) using molecular line data from Schöier et al. (2005). A synthetic spectrum of HCN(1–0) was calculated from the LRT simulation. In principle, the systemic velocity \(v_{\text{LSR}}\) is an additional parameter. We have assumed the values of 36.1 km s\(^{-1}\) (SMM1 North) and 34.8 km s\(^{-1}\) (SMM1 South) derived from the positions of the spectral features. The consistency between calculated and observed spectra was evaluated with a \(\chi^2\)-criterion and took into account all the velocity channels of the combined HCN(1–0) spectrum.

To search for the best set of the model parameters, we used Powell’s minimization algorithm (Press et al. 1992). We had to specify parameter ranges for the search for the best-fit model. In our simulations, we used the ranges given in Table 3 to derive the best-fit parameter sets. The ranges resulted from several runs where we specified parts of the adjacent parameter space and did not find good reproductions of the observed spectra. Though unlikely, we cannot exclude that additional compatible sets of parameters exist. In order to assure that the minimization routine was not trapped in a local minimum, we repeated the calculations starting with several sets of initial parameters. The best-fit spectra obtained for the one-layer model with the corresponding parameters are shown in Figure 6 in the top row.

In the case of SMM1 North, the observed line ratios were reproduced fairly well. We found a degeneracy between the hydrogen density, the kinetic temperature, and the HCN column density, and therefore we set \(n_{H_2} = 10^5\) cm\(^{-3}\). This resulted in \(T_{\text{kin}} = 10\) K and \(N_{\text{HCN}} = 7 \times 10^{12}\) cm\(^{-2}\). Furthermore, given the assumption that the observed HCN(1–0) components are indeed single-peaked and relatively narrow, the effect of the regular and turbulent velocities cannot be distinguished. Therefore, we set the regular velocity to zero. The derived value of the turbulent velocity is 0.4 km s\(^{-1}\). Note that in contrast to the study of Gonzalez-Alfonso & Cernicharo (1993), we did not have to introduce any regular velocity to explain the “anomalous” line ratios. The obtained ratios naturally appeared as a result of the non-LTE excitation in the subcritical density.

In the case of SMM1 South, the one-layer model could not reproduce the maximal intensities and the strength of the self-absorption dips at the same time. We show one representative spectrum from the one-layer model in Figure 6.

A natural way to reproduce the observed spectrum of SMM1 South is to include a low-density envelope in the model which should lead to self-absorption. We checked this by constructing a “two-layer” model with 5+5 parameters, and chose a configuration where a static core \((v_{\text{rad}} = 0)\) is surrounded by a spherically symmetric, homogeneous envelope. The increased number of parameters makes it difficult to identify a best set through the minimization routine. Therefore, we fixed some of the parameters based on the following arguments. First, we assumed that the hydrogen density in the core is higher while in the envelope it is lower than the critical density for HCN (1–0). Given this assumption, we expect the formation of strong self-absorption dips if the HCN column density in the envelope is high enough. We set the densities to \(n_{H_2}^{\text{env}} = 10^6\) cm\(^{-3}\) and \(N_{\text{HCN}}^{\text{env}} = 10^3\) cm\(^{-2}\). We also fixed the temperature in the envelope \(T_{\text{kin}}^{\text{env}} = 10\) K assuming that it is not heated by the inner (most probably warmer) part of the core, for which we chose \(T_{\text{kin}}^{\text{core}} = 30\) K. Changes in the core temperature do not affect the derived model spectra significantly. Thus, we varied the five parameters \(N_{\text{HCN}}^{\text{env}}, v_{\text{turb}}^{\text{env}}, v_{\text{turb}}^{\text{core}}, v_{\text{rad}}^{\text{env}}, v_{\text{rad}}^{\text{core}}\), and constrained them using the minimization routine.

The best-fit spectrum obtained from the two-layer model is presented in Figure 6 (bottom). The two-layer model could reproduce the intensity, the strong self-absorption dips, and asymmetry of the observed spectrum quite well. The line wings may stem from outflowing gas, or also be due to a more complex velocity profile not incorporated in the model. The important outcome of this model can be summarized as follows: first, the strong self-absorption in the line profiles can be reproduced by the high-density core together with the low-density envelope. Second, the asymmetry of the line profiles can be explained by the infalling envelope (we got \(v_{\text{rad}}^{\text{env}} = -0.14\) km s\(^{-1}\)), given the relatively high turbulent velocities in the core \((v_{\text{turb}}^{\text{core}} = 1.7\) km s\(^{-1}\)) and in the envelope \((v_{\text{turb}}^{\text{env}} = 0.5\) km s\(^{-1}\)). However, this configuration is not the only way to fit the line asymmetries. In particular, we were able to reproduce the line asymmetries by the combination of an expanding core and a static envelope because of the similar relative velocities. We consider this scenario implausible, though, because of the short outflow timescales.

Finally, we stress that the considered simple models did not reliably constrain the other parameters of the cores, but they illustrated that the observed spectra can indeed be explained.

### Table 3

| Parameter Model          | Parameter | SMM1 North | SMM1 South |
|--------------------------|-----------|------------|------------|
| \(n_{H_2}\) (cm\(^{-3}\)) | 10\(^5\)   | 10\(^3\)–10\(^5\) |
| \(T_{\text{kin}}\) (K)    | 10–50     | 10–50     |
| \(N_{\text{HCN}}\) (cm\(^{-2}\)) | 10\(^{12}\)–10\(^{15}\) | 10\(^{13}\)–10\(^{15}\) |
| \(v_{\text{turb}}\) (km s\(^{-1}\)) | 0–1.0     | 0–1.0     |
| \(v_{\text{rad}}\) (km s\(^{-1}\)) | 0         | 0         |

Two-Layer Model for SMM1 South

| Parameter | Core | Envelope |
|-----------|------|----------|
| \(n_{H_2}\) (cm\(^{-3}\)) | 10\(^6\) | 10\(^3\) |
| \(T_{\text{kin}}\) (K) | 30 | 10 |
| \(N_{\text{HCN}}\) (cm\(^{-2}\)) | 10\(^{12}\)–10\(^{15}\) | 10\(^{13}\)–10\(^{15}\) |
| \(v_{\text{turb}}\) (km s\(^{-1}\)) | 0–3.0 | 0–1.0 |
| \(v_{\text{rad}}\) (km s\(^{-1}\)) | 0 | -1–1 |
Figure 6. Model illustration, observed and modeled HCN(1–0) spectra toward the two SMM1 cores. In the top row, the one-layer model is illustrated and the resulting best-fit spectra (red curves) are shown with the corresponding model parameters. The bottom row shows the two-layer model and the resulting best fit of the SMM1 South spectrum (red curve) as well as the corresponding model parameters. Parameters that have been fixed are marked with a preceding asterisk (*).

(A color version of this figure is available in the online journal.)

Theoretically, in order to get more reliable information about the core properties, one has to consider a set of molecular lines and transitions together with more physical models of the source. Unfortunately, the available data, in particular the HCO⁺(1–0) measurements, are not sufficient to enable this. Indeed, if we used HCO⁺(1–0) in addition to HCN(1–0) in our fitting routine, we would have to incorporate two more parameters for the HCO⁺ abundance (in the core and in the envelope), while HCO⁺(1–0) alone will not allow us to further constrain the excitation conditions. For the latter, at least a few more transitions of HCO⁺ or its isotopomers were necessary. On the other hand, a more physical model of the core (e.g., with smooth distributions) has more parameters to fit which makes such a model even more uncertain. Thus, the usage of more sophisticated models is required when detailed spectral maps of the sources are available.

4.3.3. Collapse of SMM1 South

The modeling of the HCN emission showed that the spectrum of SMM1 South can be explained with a collapse of the core. From the resulting velocity, we calculated estimates for the mass infall rate using $dM/dt \approx M/v_{in}/r$. For SMM1 South, $v_{in} = 0.14 \text{ km s}^{-1}$ is the regular velocity of the envelope in the two-layer model. Together with the mass and radius from Table 1 this gave an infall rate of $3 \times 10^{-5} M_\odot \text{ yr}^{-1}$. This is consistent with the mass outflow rates, but is only a crude estimate.

4.3.4. Internal Turbulence

Additional parameters we obtained from the HCN emission are the internal turbulent velocities of the cores that reproduced the observed line widths. However, in both cases rotational motions, more complex velocity profiles, and also outflows may contribute to the line widths. Such effects were not considered in our models. In the case of SMM1 South, the fitted model shows a very turbulent core and less turbulence in the envelope. When compared to the isothermal sound speed of around 0.2 km s$^{-1}$ for cold cores ($T \approx 20$ K), the core turbulence of 1.7 km s$^{-1}$ is highly supersonic. The turbulent velocity in the envelope of 0.5 km s$^{-1}$ is on the scale of the sound speed but still in the supersonic regime. The SMM1 North HCN spectrum indicates a more quiescent state of this core. The line widths are reproduced with a turbulent velocity of 0.4 km s$^{-1}$.

5. SUMMARY AND CONCLUSIONS

We have investigated the onset of star formation in the massive cold clump ISOSS J18364–0221 SMM1. The derived
results regarding the clump fragmentation, the core and outflow properties, and the collapse indications are summarized as follows.

1. Two compact, embedded cores are the only objects we identified. Thus, this clump shows little fragmentation, but seems to rather produce a low number of compact objects.

2. The cores dubbed SMM1 North and South are of about 10,000 and 9000 AU radius. The dust temperatures are 15 and 22 K and they have masses of about 15 and 10 $M_\odot$, respectively. SMM1 South harbors an infrared source not detected at 8, but at 24 and 70 $\mu$m. The luminosity of SMM1 South is about 180 $L_\odot$ and a molecular outflow is detected in its vicinity. SMM1 North lacks infrared emission, but a second molecular outflow is emerging from this core. The luminosity of SMM1 North is approximately 20 $L_\odot$. Both outflows appear collimated and we derived lower outflow mass limits of about 0.2 and 0.3 $M_\odot$ of presumably entrained gas, and mass outflow rates of about $4 \times 10^{-5} M_\odot$ yr$^{-1}$. In Figure 7, we show a schematic illustration of these results.

3. We detected filaments of shock-excited $H_2$ emission at 2.122 $\mu$m toward the lobes of the SMM1 South molecular outflow, and also at distances up to 4.6 pc from SMM1. Each filament is roughly aligned with one of the outflow axes. They are possibly tracing the outflow-generating jets, and the dynamical timescales we derived are consistent with those of the molecular outflows considering the uncertain jet velocities. For both molecular outflows, ages of less than $10^4$ yr were found.

4. SMM1 South is bright in HCN(1–0) and our modeling results support that the core is collapsing. We got an infall velocity of 0.14 km s$^{-1}$. This results in a mass infall rate estimate of $3 \times 10^{-5} M_\odot$ yr$^{-1}$. For both cores the spectra can be interpreted with turbulent internal motions, and in the case of SMM1 South the innermost part appears highly supersonic.

Both SMM1 North and South are more massive than typical low-mass dense cores and embedded in the presumably contracting 75 $M_\odot$ SMM1 clump. This suggests that the two cores harbor protostellar seeds that may become intermediate-to high-mass stars. The presence of a 24 $\mu$m source, a very turbulent central region, and the jet features at large distances to the core support that SMM1 South is more evolved than SMM1 North. We interpret it as having an embedded young protostar that constitutes the driving source of the outflow. The outflows as well as the infall indicate that it is accreting. The associated outflow indicates that SMM1 North is also a star-forming core, and the outflow energetics are similar. However, the forming object remains undetected, and the relatively low level of turbulence implies that it has only marginally affected the surrounding core. The presumed difference in evolution of the forming objects contrasts with the similar sizes, densities, and outflow properties of the cores. These findings suggest a rapid evolution of the luminosity as predicted for high accretion rates (Yorke 2008).

In comparison to the core collapse simulations of Krumholz et al. (2007), we find that the luminosity of SMM1 South would be reached at a stage where the embedded protostellar mass is around 0.3 $M_\odot$. Accretion onto the protostar is the dominant luminosity source, and they find an accretion rate on the order of $10^{-4} M_\odot$ yr$^{-1}$ from directly after the formation of the protostar until this stage. The resulting timescale of about 3000 yr is consistent with the outflow timescales. Also the mass outflow rate as well as the infall rate estimate may be consistent with the high accretion rate. SMM1 North is less luminous, and hence the protostellar mass would be even lower, but may still be consistent with a high accretion rate in their model. However, the formation of outflows is not incorporated therein.

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