# MILLIMETRIC AND SUBMILLIMETRIC OBSERVATIONS OF IRAS 05327+3404 "HOLOEA" IN M36

O. MORATA<sup>1,2</sup>, Y.-J. KUAN<sup>2</sup>, P. T. P. Ho<sup>1</sup>, H.-C. HUANG<sup>2</sup>, E. A. MAGNIER<sup>3</sup>, AND R. ZHAO-GEISLER<sup>2</sup> <sup>1</sup>Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; omorata@asiaa.sinica.edu.tw

Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; omorata@asiaa.sinica.edu.tw <sup>2</sup> Department of Earth Sciences, National Taiwan Normal University, 88 Section 4, Ting Chou Road, Taipei 116, Taiwan <sup>3</sup> Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA

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# ABSTRACT

The transition between the protostar, Class I, and the pre-main-sequence star, Class II, phases is still one of the most uncertain, and important, stages in the knowledge of the process of formation of an individual star because it is the stage that determines the final mass of the star. We observed the young stellar object "Holoea," associated with IRAS 05327+3404, which was classified as an object in the transition between the Class I and Class II phases with several unusual properties, and appears to be surrounded by large amounts of circumstellar material. We used the SMA and BIMA telescopes at millimeter and submillimeter (submm) wavelengths to observe the dust continuum emission and the CO (1–0) and (2–1), HCO<sup>+</sup> (1–0) and (3–2), and HCN (1–0) transitions in the region around IRAS 05327+3404. We detected two continuum emission peaks at 1.1 mm: SMM 1, the submm counterpart of IRAS 05327+3404, and SMM 2, ~6 arcsec to the west. The emissions of the three molecules show marked differences. The CO emission near the systemic velocity is filtered out by the telescopes, and CO mostly traces the high-velocity gas. The HCO<sup>+</sup> and HCN emissions are more concentrated around the central parts of the region, and show several intensity peaks coincident with the submm continuum peaks. We identify two main molecular outflows: a bipolar outflow in an E–W direction that would be powered by SMM 1 and the other in a NE direction, which we associate with SMM 2. We propose that the SMM sources are probably Class I objects, with SMM 1 in an earlier evolutionary stage.

*Key words:* ISM: clouds – ISM: individual objects (IRAS 05327+3404) – ISM: jets and outflows – ISM: molecules – stars: protostars

Online-only material: color figures

## 1. INTRODUCTION

The process of the formation of an individual star has been extensively studied and modeled in recent decades, which has resulted in a well-supported general picture (see, e.g., Lada & Wilking 1984; Adams et al. 1987; André et al. 1993) that describes the evolution of a young stellar object (YSO) from a pre-stellar core to a main-sequence star along several stages (Ward-Thompson 1996). These steps can be divided into two main phases. First, there would be an embedded phase, in which a dense core in a molecular cloud collapses to form a heavily obscured, hydrostatic protostar, invisible to optical wavelengths, which is surrounded by a progenitor disk and a massive envelope that proceeds to accrete the majority of its mass while simultaneously driving a highly collimated bipolar outflow. This would be followed by a revealed phase after the accretion of material has stopped and once the YSO has acquired most of its final mass. The enshrouding dust is progressively cleared away and a pre-main-sequence star, surrounded by a thinning disk, becomes visible to optical and near-infrared wavelengths. In time, this protostar will complete its Kelvin-Helmholtz contraction onto the main sequence.

A very interesting and still uncertain step in this process is the transition from protostar to pre-main-sequence star—between the embedded (Class I) and revealed (Class II) phases—which is accompanied by the action of energetic molecular outflows and ionized jets (Magnier et al. 1999a). This stage approximately marks the end of the mass accretion onto the protostar, which determines the final mass of the star. The mechanism that brings about this end is not yet well understood, but probably involves the action of the outflows on the surrounding dust and gas

envelope. Thus, the observation of objects that happen to be found at this stage of the evolution is of fundamental importance to understand the physics of the processes involved and for the modeling of the disk and envelope structures around YSOs. In this paper, we present results of millimeter interferometric studies of one of these objects.

The source nicknamed "Holoea," Hawaiian for "flowing gas," is a YSO associated with IRAS 05327+3404. It was discovered in optical observations of the Galactic open cluster M36 in Auriga by Magnier et al. (1996), although it is probably not associated with M36 and may be a distant member of the nearby S235 region. The distance to the object is then somewhat uncertain, ranging from the 1.2 kpc adopted by Hron (1987) for M36 to the 1.6 kpc for S235 (Blitz et al. 1982). We adopt a distance of 1.2 kpc. IRAS 05327+3404 drives a powerful ionized outflow, seen in both CO (2-1) and optical spectra, with unusually high velocity ( $\sim 650 \text{ km s}^{-1}$ ) for a low-mass star. The structure of IRAS 05327+3404 is not yet clear (see Magnier et al. 1999b). It could be a binary system with a central star of optical spectral type K2 III, which is probably an FU Orionis star similar to L1551 IRS 5 (Magnier et al. 1999b), and a still embedded young star powering the outflow.

The young star was classified (Magnier et al. 1999a, 1999b) as a transitional YSO between Class I and Class II, because of its rising spectral energy distribution (SED) and molecular bipolar outflow as well as its visible central star and ionized outflow. The SED also shows the presence of large amounts of circumstellar material, which, according to optical and near-IR observations of the reflection nebula, seems to be arranged in a disk with a relatively wide central hole of  $\sim 33^{\circ}$  opening angle. The ionized flow, the CO outflow, and the hole are all

roughly aligned and tilted by  $\sim 45^{\circ}$  to our line of sight (Magnier et al. 1996). Additionally, the brightness of the central star has increased >1.5 mag since the 1954 POSS plates. Magnier et al. (1999b) suggest that the source might be in the process of becoming exposed and hypothesized that the unusually wide SED could be due to the relative isolation of IRAS 05327+3404, which allowed the formation of a large circumstellar disk with high angular momentum without being disrupted by external sources. Thus, this object seems to be a good candidate to study the transition from the Class I to the Class II phase in the evolution of YSOs. Subsequent 3.6 cm Very Large Array (VLA) observations by Anglada & Rodríguez (2002) detected a source, named VLA 2, inside the error ellipsoid of IRAS 05327+3404, which coincides within  $\sim 1$  arcsec of the optical position of Magnier et al. (1996). H<sub>2</sub>O maser emission surveys by Wouterloot et al. (1993), Codella et al. (1995), and Sunada et al. (2007) did not detect any maser emission near IRAS 05327+3404.

The structure of this paper is as follows: in Section 2, we describe the Submillimeter Array (SMA) interferometer observations made at 1 mm and the BIMA interferometer observations carried out in the 3 mm band, in Section 3, we present the results obtained for the 261 GHz continuum emission and of the CO (2–1), HCO<sup>+</sup> (2–1), CO (1–0), HCO<sup>+</sup> (1–0), and HCN (1–0) lines; and in Section 4, we discuss the results and propose a picture for the structure of the gas in the region. Section 5 gives our conclusions.

# 2. OBSERVATIONS

## 2.1. SMA Observations

The observations of IRAS 05327+3404 were performed with the eight-element SMA array (Ho et al. 2004) in Mauna Kea, HI as part of a filler-time project in 2011 November and 2012 January in the compact and sub-compact configurations, respectively. The half-power beam width of the 6 m antennas is 54 arcsec at 230 GHz, and 41 arcsec at 261 GHz. Maps were obtained with the visibility data weighted by the associated system temperatures using natural weighting. Baselines range from 6 to 53 k $\lambda$  and from 6 to 40 k $\lambda$ , respectively. The resulting synthesized beam sizes are ~2″.5–6″.5. The total onsource observing time was 0.99 hr for the 2011 November observations and 4.62 hr for the 2012 January observations. The central position of the maps for both tracks was located at  $\alpha$ (J2000) = 5<sup>h</sup>36<sup>m</sup>05<sup>s</sup>90,  $\delta$ (J2000) = +34°06′12″.1.

The receivers were tuned to a rest frequency of 230.53797 GHz for the observations in 2011 November and 267.55762 GHz for the observations in 2012 January, and were Doppler tracked to a velocity  $V_{\rm LSR}$  of -21.7 km s<sup>-1</sup>. In the 230.5 GHz observations, the correlator was configured to observe three spectral windows to include the CO (2–1), <sup>13</sup>CO (2–1), and C<sup>18</sup>O (2–1) lines, with 203 kHz (0.26 km s<sup>-1</sup>) resolution; 3.94 GHz were dedicated to observe the 1.3 mm continuum in both the upper and lower sidebands (USB and LSB). For the 267.5 GHz observations, the correlator was configured to observe four spectral windows: three windows with 203 kHz (0.23 km s<sup>-1</sup>) spectral resolution, including the HCO<sup>+</sup> (3–2) line, and one window with 812 kHz (0.91 km s<sup>-1</sup>). 3.94 GHz were dedicated to observe the 1.3 mm continuum in both the USB and LSB.

The data were reduced using the MIR and MIRIAD (Sault et al. 1995) packages. The data were flagged for bad channels, antennas, weather, and pointing. We used 3C84 and BL Lac objects as bandpass calibrators for the 2011 November track and 3C279, Mars, and 0927+390 for the 2012 January track. Gain calibrators were 0646+448 and 0530+135 for the 2011 November data and 3C111 for the 2012 January data. Absolute flux calibration was done using observations of Uranus in both tracks.

#### 2.2. BIMA Observations

The observations of IRAS 05327+3404 were carried out with the BIMA array at the Hat Creek Radio observatory during six periods, using six antennas in the C configuration in 1995 August (twice) and 1995 September, and using nine antennas in the H configuration in 1995 December and 1996 May (twice). Maps were made at 88 and 115 GHz with the visibility data weighted by the associated system temperatures, using natural weighting and applying the primary beam correction. The *uv*-coverage was ~1.2–37 k $\lambda$ , and the resulting synthesized beam sizes are ~6–10 arcsec. The half-power beam width of the BIMA antennas is 120 arcsec at 100 GHz. The central position of the maps was also located at  $\alpha$ (J2000) = 5<sup>h</sup>36<sup>m</sup>05<sup>s</sup>90,  $\delta$ (J2000) = +34°06′12″.1.

Two frequency setups were used, centered at 88 and 115 GHz, respectively. The target molecular lines were CO (1–0) at 115.27120 GHz, HCO<sup>+</sup> (1–0) at 88.18852 GHz, and HCN (1–0) at 88.63185 GHz. The digital correlator was configured to simultaneously observe several molecular line transitions in the USB at spectral resolutions of 97.7 and 390.6 kHz channel<sup>-1</sup>, which correspond to velocity resolutions of 0.25 and 1.00 km s<sup>-1</sup> for CO, and 0.32 and 1.28 km s<sup>-1</sup> for HCO<sup>+</sup> and HCN. CO lines were observed in one period in 1995 August and in 1995 September.

Calibration and data reduction were performed using the MIRIAD software package. The source 0530+135 was used as phase calibrator, while Mars, Saturn, 3C273, and 0530+135 were used as bandpass calibrators. The molecular line transitions tuned to the LSB did not show any emission.

## 3. RESULTS

#### 3.1. Continuum Observations

#### 3.1.1. 261 and 224 GHz Continuum

Figure 1(a) shows the continuum map of IRAS 05327+3404 obtained with the SMA from the combination of the continuum data from the USB and LSB at a nominal frequency of 261 GHz. The only emission over  $3\sigma$  is located in the central 10 arcsec of the map. The emission is extended in an east–west direction with a slightly NW bend in the western tip. The emission peak (SMM 1) is located at ~1″1 S of the catalog position of IRAS 05327+3404 with an intensity of 28.7 mJy beam<sup>-1</sup> (~21 $\sigma$ ). There is a secondary emission peak (SMM 2) located at an offset,  $\Delta\alpha$ ,  $\Delta\delta = (-5″.2, +3″.1)$  from SMM 1, with an intensity of 17.4 mJy beam<sup>-1</sup> (~13 $\sigma$ ). The separation between the two peaks is ~6″.1, about ~7300 AU at the assumed distance to the source, and it probably indicates the presence of two objects. The total flux inside the half-intensity contour encompassing both emission peaks is 33.4 mJy.

We tried to see if the continuum emission could be described by the superposition of two elliptical Gaussians centered around the position of the two emission peaks. Table 1 shows the parameters of the two 2D Gaussians that best reproduce the continuum emission over  $3\sigma$ : the one corresponding to SMM 1 is elongated in an NE–SW direction, while the other corresponding

 Table 1

 Parameters of the 2D Gaussians Fitted to the 261 GHz Continuum Map

Source	R.A. (J2000)	Decl. (J2000)	Gaussian <sup>a</sup> Size	P.A.	$I_{\text{peak}}^{\text{b}}$ (Jy beam <sup>-1</sup> )	Flux <sup>c</sup> (Jy)	Size <sup>d</sup> (arcsec)	Mass <sup>e</sup> $(M_{\odot})$	$N({ m H_2})^{ m f}$ (10 <sup>23</sup> cm <sup>-2</sup> )	$n({ m H_2})^{ m f}$ (10 <sup>6</sup> cm <sup>-3</sup> )
SMM 1	5:36:05.93	34:06:11.5	$4''_{}0 \times 2''_{}6$	+66°8	0.028	0.039	3.2	1.5	2.1	5.3
SMM 2	5:36:05.45	34:06:14.2	2".5 × 2".3	-88°6	0.016	0.020	2.4	0.8	1.9	6.6

Notes.

<sup>a</sup> Deconvolved major and minor axes.

<sup>b</sup> Peak intensity calculated from the fit of two 2D Gaussians to the continuum emission.

<sup>c</sup> Total integrated flux inside the 2D Gaussians resulting from the fit of the continuum emission.

<sup>d</sup> Effective diameter of the condensation from  $\sqrt{\theta_a \theta_b}$ , where  $\theta_a$  and  $\theta_b$  are the lengths of the major and minor axes of the Gaussian, respectively.

<sup>e</sup> Total mass calculated from the flux density integrated over the fitted 2D Gaussian, using the expression from Frau et al. (2010), for a distance of 1.2 kpc.

<sup>f</sup>  $N(H_2)$  and  $n(H_2)$  are the values of the column and volume densities averaged over the size of the fitted 2D Gaussian, respectively, calculated using the expressions from Frau et al. (2010), assuming dust temperature,  $T_{dust} = 15$  K, a standard dust-to-gas ratio of 100, a dust absorption coefficient at a frequency of 261 GHz,  $\kappa_{261} = 0.0089$  cm<sup>2</sup> g<sup>-1</sup>, taken as the value for dust grains with thin ice mantles for a volume density of  $\sim 5 \times 10^5$  cm<sup>-3</sup> (Ossenkopf & Henning 1994).



**Figure 1.** (a) Map of the 1.1 mm continuum emission in the IRAS 05327+3404 region. Contours are -3, 3, 6, 9, . . . times the rms of the map, 1.35 mJy beam<sup>-1</sup>. The cross marks the position of "Holoea," IRAS 05327+3404, and the filled (white) circle marks the position of the 3.6 cm VLA 2 source detected by Anglada & Rodríguez (2002). The central ellipse marks the error ellipse of the *IRAS* source. The beam size is  $\sim 6'/2 \times 4''_2$ , with a position angle, P.A. =  $73^{\circ}3$ . (b) Same as (a) for the 224 GHz continuum after applying a *uv* tapering of  $36 \text{ k}\lambda$ . Contours are -3, 3, 4 times the rms of the map, 2.8 mJy beam<sup>-1</sup>. The beam size is  $\sim 6'/8 \times 4''_2$ , with P.A. =  $82^{\circ}0$ .

to SMM 2 is almost circular in shape. The central positions, which we adopt as the nominal positions of the submillimeter (submm) sources, are slightly displaced with respect to the

visual identification we had made, but well inside our angular resolution. The total integrated fluxes we measure are 39.1 and 19.9 mJy, respectively.

The catalog position of IRAS 05327+3404 is located  $\sim$ 0.8 arcsec NW from SMM 1, while the unresolved 3.6 cm VLA 2 source detected by Anglada & Rodríguez (2002) is located  $\sim$ 0.5 arcsec SW of SMM 1. The uncertainty in the determination of the VLA position is probably on the order of  $\sim$ 1 arcsec, given the beam size and signal-to-noise ratio of the centimeter observations. We would also expect that if the unresolved VLA 2 source had any significant contribution from SMM 2, the centroid of the centimeter emission would be displaced >1 arcsec to the NW. Thus, given that the positions of the infrared and centimeter emissions coincide within  $\sim$ 1 arcsec from SMM 1, we conclude that SMM 1 is the submm counterpart of IRAS 05327+3404 and VLA 2.

Figure 1(b) shows the continuum map obtained by combining the USB and LSB continuum data in the 230.5 GHz track, with a resulting nominal frequency of 224 GHz, after applying a *uv* tapering of 36 k $\lambda$ . We do not find any extended emission on the map obtained with natural weighting. After applying the tapering, we find a condensation ~7.5 × 5.5 arcsec, coinciding with the position of SMM 1, with an intensity peak of 12.7 mJy beam<sup>-1</sup> and an estimated total flux of 18.9 mJy (measured at the  $2\sigma$  contour).

## 3.1.2. 3 mm Continuum

The lines tuned up in the LSB of both of the frequency setups used with the BIMA telescope, at 85 and 112 GHz, respectively, were too weak to be detected. The 768 channels available in four windows in the LSB could then be used to try to detect continuum emission. Unfortunately, the bandwidth was probably too narrow to detect any emission over  $3\sigma$  ( $1\sigma$  is 3.8 and 20 mJy beam<sup>-1</sup> respectively) in the region. Adding the visibilities at the two frequencies in order to get a better signal-to-noise ratio using a multi-frequency cleaning did not improve the results and we failed to detect any emission over  $3\sigma$  ( $1\sigma = 4.9$  mJy beam<sup>-1</sup>).

#### 3.2. Spectral Observations

## 3.2.1. HCO+ (3-2)

Figure 2 shows the integrated intensity map of the  $HCO^+$  (3–2) emission obtained with the SMA. The emission is





**Figure 2.** Integrated intensity map of the HCO<sup>+</sup> (3–2) emission in the velocity range from -23.99 to -19.21 km s<sup>-1</sup>, with a resulting mean velocity of -21.6 km s<sup>-1</sup>. Contours are -3, 3, 6, 9, ... times the rms of the map, 0.12 Jy beam<sup>-1</sup>. The beam size is  $\sim 6''_{...3} \times 4'_{...0}$ , with P.A. =  $73^\circ_{...3}$ . The triangles mark the positions of the emission peaks in the 261 GHz continuum map, SMM 1 and SMM 2 (Figure 1(a)).

elongated in the NW–SE direction, with two partially resolved condensations. The more intense (peak intensity 3.38 Jy beam<sup>-1</sup>) coincides with the position of the 1.1 mm continuum emission peak SMM 1. The second condensation (peak intensity 1.43 Jy beam<sup>-1</sup>) is located ~8.5 arcsec NW of the emission peak. Both condensations are connected by low-level emission at more than the  $3\sigma$  level of the map. The continuum emission peak SMM 2 is located approximately at the neck of this bridge.

Figure 3 shows the channel maps of the HCO<sup>+</sup> (3–2) emission from -23.8 to -19.2 km s<sup>-1</sup>. The two condensations found in the integrated intensity map (Figure 2) are present in the central velocity channels. The central condensation is seen in all the channels containing any emission, while there is emission over a  $3\sigma$  level ~7.5 arcsec to the NW only from -22.17 to -20.58 km s<sup>-1</sup>. This emission coincides with the secondary condensation found in the integrated intensity map and seems to drift slightly from the SW to the NE. There is a third condensation only found in the more blueshifted emission (from -22.63 to -22.17 km s<sup>-1</sup>) just south of the peak of the secondary condensation, located  $\sim$ 5.5 arcsec to the NW of SMM 1, and coinciding with the position of SMM 2 (see Figure 1). All three condensations are connected by emission at levels  $>6\sigma$  for velocities closer to the systemic velocity. We also find some weak extended emission elongated in an N-S direction just south of SMM 1 at the systemic velocity channel  $(-21.72 \text{ km s}^{-1})$  and some toward the SW from a position in-between SMM 1 and SMM 2 at -22.53 km s<sup>-1</sup>.

## 3.2.2. HCO+ (1-0)

Figure 4 shows the integrated intensity map of the emission of the HCO<sup>+</sup> (1–0) transition obtained with BIMA. The more intense emission is oriented in the NW–SE direction, enclosing the emission peaks found in the HCO<sup>+</sup> (3–2) maps. There are two emission peaks, the most intense one being located to the

NW of SMM 1, at  $(\Delta \alpha, \Delta \beta) = (-6.4, +4.2)$ , and seeming to include the two northwestern peaks found in the HCO<sup>+</sup> (3–2) maps. The second emission peak coincides within uncertainties with SMM 1.

The channel maps of the HCO<sup>+</sup> (1–0) line (see Figure 5) also show the three condensations found in the (3–2) line, surrounded by more extended emission, which always connects the three main peaks. The central condensation is mainly found from -22.42 to -21.43 km s<sup>-1</sup>, and in particular around the systemic velocity. The emission toward the NW is predominantly found in the redshifted velocities, from -21.76 to -20.78 km s<sup>-1</sup>. The emission around SMM 2 is particularly intense for the blueshifted velocities, from -22.42 to -21.76 km s<sup>-1</sup>. There are other emission features in the blueshifted channels, which were also seen in the HCO<sup>+</sup> (3–2) channel maps: an elongation in a N–S direction south of SMM 1, with a local emission peak; and an elongation to the SW from a point in between SMM 1 and SMM 2. There is also a weak emission patch elongated to the NE of SMM 1 at -22.42 km s<sup>-1</sup>.

There is also fainter emission at ~50 arcsec NW of SMM 1, approximately coincident with emission also found in HCN (1–0) and CO (1–0) (see Sections 3.2.3 and 3.2.4, respectively). This emission patch only appears in the velocity range -22.09 to -21.11 km s<sup>-1</sup>, but the emission peak moves ~10 arcsec from W to E as the velocity changes from redshifted to blueshifted channels.

#### 3.2.3. HCN (1-0)

The emission of the HCN (1–0) line obtained with the BIMA telescope (Figure 6) is very concentrated in the central part of the map, in the shape of an "L" that connects the two continuum peaks and the NW HCO<sup>+</sup> (3–2) emission peak. None of these three emission peaks coincides with the HCN emission peak, which is located  $\sim$ 4″ to the NW of SMM 1, midway between SMM 1 and SMM 2. The NW HCO<sup>+</sup> (3–2) peak is seen as an emission plateau to the N. There is also faint emission at  $\sim$ 50 arcsec NW of IRAS 05327+3404, coinciding with the HCO<sup>+</sup> (1–0) emission patch.

Figure 7 shows the channel maps of the emission of the HCN (1–0) line in the range from -22.48 to -20.82 km s<sup>-1</sup>. The emission tends to be very concentrated and shows some similarities to the HCO<sup>+</sup> channel maps. The HCN (1–0) emission close to SMM 2 is predominantly redshifted to the N, closer to the position of the NW HCO<sup>+</sup> (3–2) peak, and predominantly blueshifted to the S of the source. Only the central channel maps show any (weaker) emission around the position of SMM 1. The central velocity channel map also shows a weak condensation or local emission peak ~10 arcsec south of SMM 1, approximately at the position of a similar condensation found in the channel maps of HCO<sup>+</sup>.

#### 3.2.4. CO (1-0)

The map of the CO (1–0) emission obtained with BIMA (Figure 8) shows a distribution very different from the maps of HCO<sup>+</sup> and HCN. The CO emission is mainly found in an east–west strip passing toward the west through the position of SMM 1 and then bending in a SW direction west of SMM 1. The main emission peak is located  $\sim$ 3 arcsec NE of SMM 1. There is a small spur in the emission in the NW direction from the position of IRAS 05327+3404, which roughly corresponds to the more intense emission found in the HCO<sup>+</sup> (1–0) and HCN (1–0) integrated intensity maps. A weaker emission peak is found  $\sim$ 18 arcsec east of SMM 1. There is also a weak



**Figure 3.** Channel maps of the HCO<sup>+</sup> (3–2) emission in the velocity range from -23.54 to -19.21 km s<sup>-1</sup>. Contours are -3, 3, 6, 9, ... times the rms of the map, 0.26 Jy beam<sup>-1</sup>. The beam size is  $\sim 6''.3 \times 4''.0$ , with P.A. = 73°.3. The triangles mark the positions of the emission peaks in the 261 GHz continuum map (Figure 1(a)) and the squares mark the positions of the emission peaks of the integrated intensity map of HCO<sup>+</sup> (3–2). The velocity, in km s<sup>-1</sup>, of each map is indicated in the upper left corner of each panel.

emission peak at ~15 arcsec SW of SMM 1, in a direction similar to some weakly extended emission found in the HCO<sup>+</sup> channel maps. There are several clumps of emission in the NE direction from IRAS 05327+3404, with a position angle (P.A.) ~9°. Another patch of emission is located ~50 arcsec NW of IRAS 05327+3404, coinciding with similar emission patches found in the HCO<sup>+</sup> (1–0) and HCN (1–0) maps.

If we compare our observations with the James Clerk Maxwell telescope CO (2–1) integrated intensity map of Magnier et al. (1999b), our observations cover the more central regions closer to IRAS 05327+3404. Taking into account the lower angular resolution of the single-dish map, the distribution of the BIMA emission seems to be similar, but it is also clear that we are probably missing some extended emission. The CO (1–0) emission that we find along the NE direction follows the same direction as the NE outflow that was identified by Magnier et al. (1999b). We are tracing the innermost part of this outflow

and the clumps we identify coincide with local intense emission in the map of Magnier et al. (1999b).

Figure 9 shows the four-channel (0.25 km s<sup>-1</sup> channel<sup>-1</sup>) averaged intensity maps of CO centered on the position of IRAS 05327+3404. The channel at the systemic velocity,  $v_{LSR} = -21.77$  km s<sup>-1</sup>, does not have any CO emission in the central positions. This is probably due to an extended gas structure at this position at about the systemic velocity, which is filtered by the BIMA telescope (see Section 4.4.1). On the other hand, the redshifted and blueshifted emission channel maps reveal a very complex velocity structure. In order to examine more carefully the velocity structure of the region, we show in Figure 10(a) the superposition of the integrated intensity of the redshifted and blueshifted channels with significant emission of CO and motions larger than 1 km s<sup>-1</sup> relative to the systemic velocity. We further show in Figures 10(b) and (c) the redshifted and blueshifted integrated intensity maps for the high and



**Figure 4.** Map of the integrated intensity of the HCO<sup>+</sup> (1–0) emission in the velocity range from -22.42 to -20.78 km s<sup>-1</sup>, with a resulting mean velocity of -21.60 km s<sup>-1</sup>. The contours are  $-3, 3, 4, \ldots, 7, 9, \ldots, 15, 19, 21, 22, 23, 24$  times the rms of the map, 0.060 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The beam size is  $\sim 7\%.1 \times 4\%.6$ , with P.A. = 88°.6. (A color version of this figure is available in the online journal.)

low relative velocities with respect to the systemic velocity, respectively.

Two outflows can be identified in the data: a bipolar outflow elongated in the east-west direction on both sides of SMM 1, accounting for most of the high-velocity emission in Figure 10, and the other in the NE direction, at an angle of  $\sim 9^{\circ}$ , from which we seem to detect only the redshifted lobe. These two outflows had also been detected in CO (2–1) by Magnier et al. (1999b), but at much lower angular resolution. We also find that the relative high-velocity emission is in general more compact than the relative low-velocity emission (see Figures 10(b) and (c)).

The redshifted "arm" of the east–west outflow extends eastward up to ~45 arcsec at low relative velocities and ~20 arcsec for the high relative velocities (see Figures 9 and 10). The blueshifted "arm" is more clearly seen at low relative velocities (Figure 10(c)) and it extends to ~25 arcsec westward. Figure 10(c) shows the overlap between the redshifted and blueshifted lobes over the position of SMM 1.

The NE outflow is more clearly seen at low relative velocities (see Figures 9 and 10(c)). The maps at -19.74 km s<sup>-1</sup> in Figures 9 and 10(c) also show that the outflow is not aligned with the position of SMM 1, but it is better aligned with the position of SMM 2, a few arcseconds to the west of SMM 1.

There are other velocity structures in our data that could be tracing more outflows, but they are not so clearly defined. Figure 10(b) shows redshifted emission extending  $\sim$ 10 arcsec to the SE of SMM 1, which is also found in the low-relativevelocity emission map (Figure 10(c)). The high-relative-velocity emission map also shows compact,  $\sim$ 10 arcsec, blueshifted emission elongated in an N–S direction originating from around SMM 1 (see Figure 10(b)). These redshifted and blueshifted components could be roughly aligned, but it is very difficult to tell if they belong to independent outflows or are part of emission





**Figure 5.** Channel maps of the HCO<sup>+</sup> (1–0) line in the velocity interval -22.42 to -20.78 km s<sup>-1</sup>. The first contour is 0.447 Jy beam<sup>-1</sup> with contour increments of 0.298 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The peak intensity is found at  $v_{LSR} = -21.43$  km s<sup>-1</sup>, at  $(\Delta \alpha, \Delta \beta) = (-3''5, +6'')$ , with an intensity of 2.7 Jy beam<sup>-1</sup>. The velocity, in km s<sup>-1</sup>, of each map is indicated in the upper left corner of each panel.

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

related to the two other outflows. Finally, the channel map at  $-20.75 \text{ km s}^{-1}$  shows a spur pointing away toward the SW from the central position of the map. The higher intensity contours point toward the position of SMM 2 and the NW HCO<sup>+</sup> peak, but the lower emission contours are connected to the position of SMM 1.

Additionally, we find several patches of blueshifted emission strewn around the central position, mostly in the NE and NW quarters at -22.79 and -23.80 km s<sup>-1</sup>. These emission patches probably trace more extended material partially filtered out by the telescope.

## 3.2.5. CO (2-1)

Figure 11 shows the CO (2–1) integrated intensity map obtained with the SMA in the velocity interval -25.0 to -13.8 km s<sup>-1</sup>. The only significant emission is found in an E–W direction very close to SMM 1. The emission peak is located  $\sim$ 2.5 arcsec west of SMM 1. There are not any other clearly detected structures in the map, possibly due to the limited observing time obtained with the SMA.



**Figure 6.** Map of the integrated intensity of the HCN (1–0) emission in the velocity range from -22.15 to -21.15 km s<sup>-1</sup>, with a resulting mean velocity of -21.65 km s<sup>-1</sup>. The contours are  $-3, 3, 4, \ldots, 9$  times the rms of the map, 0.065 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The beam size is  $\sim 7'.1 \times 4''.5$ , with P.A. =  $87^{\circ}$ .

Figure 12 shows the four-channel averaged intensity maps of the CO (2–1) line. The emission is mainly found around the central position of the map, along the E–W direction through the position of IRAS 05327+3404, in a way very similar to the one found in the CO (1–0) line: most of the emission is found in the redshifted velocities in an E–W strip located to the west of IRAS 05327+3404 and originating from the position of SMM 1. The channels near the systemic velocity,  $-21.76 \text{ km s}^{-1}$ , do not have any emission. There is also some weaker emission in the blueshifted maps more or less symmetrical to the emission found in the redshifted maps. The redshifted and blueshifted emissions overlap on the position of SMM 1, which supports the identification of SMM 1 as the powering source of the E–W outflow.

# 3.3. Spectra

Figure 13 shows the spectra of the five molecular lines we detected (HCO<sup>+</sup> 1–0, HCO<sup>+</sup> 2–1, HCN 1–0, CO 1–0, and CO 2–1), obtained at four selected positions of our maps: the submm peaks, SMM 1 and SMM 2, the NW HCO<sup>+</sup> peak, and the CO peak. We can appreciate the absorption dip in the CO emissions at the systemic velocities, where the HCO<sup>+</sup> and HCN emissions are found. We can also see the broadening of the HCO<sup>+</sup> (3–2) line at the SMM 1 position and, especially, at the position of the CO peak (see Section 4.3). Line widths for HCN are ~0.7–1.1 km s<sup>-1</sup>, while the line widths for HCO<sup>+</sup> are ~1.0–1.1 km s<sup>-1</sup> at the SMM 2 and NW HCO<sup>+</sup> positions, and ~1.4–2.0 km s<sup>-1</sup> at the positions of SMM 1 and the CO peak (see Section 4.3).

## 4. DISCUSSION

### 4.1. Dust Continuum Emission

We calculated the mass of the molecular gas from the 1.1 mm continuum emission, using the flux density and emission sizes



**Figure 7.** Channel map of the HCN (1–0) line in the velocity interval from -22.48 to -20.82 km s<sup>-1</sup>. The contours are -3, 3, 4, ..., 7 times the rms of the maps, 0.129 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The peak emission is found at -21.81 km s<sup>-1</sup>, at  $(\Delta \alpha, \Delta \beta) = (-3'', 0'')$ , with a flux density of 1.11 Jy beam<sup>-1</sup>. The velocity, in km s<sup>-1</sup>, of each map is indicated in the upper left corner of each panel.

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

measured from fitting two 2D Gaussians to the continuum map. Table 1 gives the  $H_2$  mass and  $H_2$  averaged column and volume densities for the two condensations found in the 261 GHz continuum map. Given the presence of stellar objects embedded in the dust emission, we assumed a dust temperature of 15 K and a dust absorption coefficient for dust with thin ice mantles at 261 GHz,  $\vec{\kappa}_{261} = 0.0089 \text{ cm}^2 \text{ g}^{-1}$  (Ossenkopf & Henning 1994). We estimate a mass of 1.5  $M_{\odot}$  for SMM 1 and 0.8  $M_{\odot}$  for SMM 2. The uncertainties in the determination of the dust temperature represent an uncertainty in the mass calculation of about a factor of two. For dust temperatures of 10–20 K, the estimated masses would be between 2.9–1.0  $M_{\odot}$ and 1.5–0.5  $M_{\odot}$ , respectively. These estimates assume a very simple spherical structure for the envelope of these sources. The real distribution of the gas around the SMM sources probably includes the presence of circumstellar disks, and the mass in the protostellar objects, which would add some uncertainties to the mass determination.

Magnier et al. (1996) gave a range of values for the bolometric luminosity of IRAS 05327+3404,  $L_{bol} \sim 41-82 L_{\odot}$ . As we have shown in Figure 1, the *IRAS* error ellipse includes both SMM 1



**Figure 8.** Integrated intensity of the CO (1–0) emission in the velocity range from -27.47 to -15.04 km s<sup>-1</sup>, with a resulting mean velocity of -21.01 km s<sup>-1</sup>. Contours are -3, 3, 6, 9, ... times the rms of the map, 0.075 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The beam size is  $\sim 7\%6 \times 6\%2$ , with P.A. = -86%4. The peak emission is located at a position ( $\Delta \alpha, \Delta \beta$ ) = (+2<sup>*m*</sup>, 0<sup>*m*</sup>) with an intensity of 2.14 Jy beam<sup>-1</sup>. (A color version of this figure is available in the online journal.)

and SMM 2, and it is conceivable that this bolometric luminosity has some contribution from both sources. In the following discussion, we assume that most of the  $L_{bol}$  is associated with SMM 1, while  $L_{bol}$  for SMM 2 is not easy to define.

In order to see if we could shed more light on the evolutionary stages of the SMM sources, we have compared the values of the mass from the submillimeter dust continuum with the envelope mass versus bolometric luminosity plot shown in Figure 1 of Bontemps et al. (1996). We define as envelope mass,  $M_{env}$ , the mass derived from our submillimeter dust emission observations. Interestingly, SMM 1 would be located in the region mainly occupied by the Class 0 sources, while SMM 2 would be at the border between the regions where Class 0 and Class I are found. The uncertainty in the determination of the envelope mass is more important to classify SMM 2 than the uncertainty in the determination of its bolometric luminosity (which we expect to be lower than that of SMM 1): a lower value for the calculated envelope mass will set SMM 2 deeper into the Class I region.

### 4.2. The Molecular Outflows: CO Emission

The results of the CO (1–0) data shown in Section 3.2.4 strongly indicate that there are several outflows in the region around IRAS 05327+3404, with probably different inclinations with respect to the plane of the sky, and, correspondingly, there should be several objects powering them. To summarize, we have clearly identified two molecular outflows: one in an east–west direction, around SMM 1, which seems to be the more promising candidate to power this outflow; and another outflow elongated in an NE direction, with P.A. = 9°, aligned with SMM 2, which is also the best candidate to power the outflow. Additionally, there are indications of other kinematic structures, but our data are not complete enough to clearly identify the nature of these structures: the "SW arm" found in the CO (1–0)

data, the compact blueshifted emission in an N–S direction north of SMM 1, and the compact redshifted emission SE of SMM 1.

Figure 14 shows the P-V cuts we took along the redshifted and blueshifted elongated structures. The missing CO emission in the central regions of the map is very apparent in the velocity range  $\sim -22.9$  to  $\sim -21.4$  km s<sup>-1</sup>, which makes it very difficult to analyze what is really happening near IRAS 05327+3404. Figure 14(a) shows the P-V cut in the direction of the optical outflow, P.A. =  $9^{\circ}$ . Similarly to what Magnier et al. (1999b) found in their data, the outflow velocity increases in relative velocity with the distance from the central region. But, we also find that at larger distances the velocity decreases with distance. On the opposite side of the central region, there is a small gradient in the redshifted velocities that probably points to the SW "outflow" found in the CO emission channel maps (see Figure 9). The CO lines are very broad at the central position with velocities from  $\sim -26.5$  to  $\sim -23$  km s<sup>-1</sup> and from  $\sim -20.5$  to  $\sim -16$  km s<sup>-1</sup>, which indicates that the CO emission is probably tracing the outflowing gas there.

Figure 14(b) shows the P-V cut obtained through the central position following an approximate east–west direction. From this P-V cut, the peak emission could be displaced ~2–3 arcsec to the east. This position would coincide with the region where HCO<sup>+</sup> shows line broadening, east of SMM 1 (see Section 4.3). This P-V diagram also reveals two hyperbolic shapes at redshifted and blueshifted channels, which could trace a possible Keplerian rotation or infall. To explore this possibility, we tried to fit the centroid position of each velocity channel of the P-V plot with simulations of a Keplerian rotating disk, within a range of central masses and inclinations. The best fits we found have  $M/\sin^2 i \sim 15-20 M_{\odot}$ , and therefore seem to be incompatible with the mass determinations we have obtained from the dust continuum emission.

There could also exist the possibility that the NE outflow and part of the "E arm" of the E–W outflow are related forming a wide opening outflow. The coincidence of the directions of the NE outflow and the strong optical jet do not seem to support this, and neither does the good agreement in the morphology and physical parameters (see Table 2 and Section 4.2.1) between the redshifted and blueshifted arms of the E–W outflow.

Magnier et al. (1999b) suspected "Holoea" to be an FU Orionis type star, which would explain the recorded increase in its luminosity in the last 40 yr. FU Orionis stars are variable stars (Herbig 1977; Hartmann & Kenyon 1996), thought to be low-mass YSOs closer to Class I protostars than to Class II T Tauri stars (Sandell & Weintraub 2001; Herbig et al. 2003), that experience a brightening of up to 6 mag over a few months, followed by a much slower fading back to their original luminosity, linked to eruptions caused by the increase of several orders of magnitude in the mass accretion rate through the circumstellar disk around the star (Hartmann & Kenyon 1996; Hartmann et al. 2004; Reipurth & Aspin 2004). A few FU Oris, such as V1057 Cyg (Herbig et al. 2003; Reipurth & Aspin 2004) and V1331 Cyg (McMuldroch et al. 1993; Quanz et al. 2007), show a shell of material around them, possibly as a consequence of an energetic mass ejection event (McMuldroch et al. 1993). We do not find these structures in our observations or clear kinematic indications of shells expanding through the molecular gas surrounding IRAS 05327+3404.

#### 4.2.1. Mass and Momentum of the CO Outflows

Table 2 shows the estimated parameters of the two main outflows identified around IRAS 05327+3404: the E–W outflow



**Figure 9.** Maps of the four-channel (0.25 km s<sup>-1</sup> channel<sup>-1</sup>) average of the CO (1–0) lines in the velocity interval from -26.85 to -15.67 km s<sup>-1</sup>. Contours are 3, 6, 9, ... times the rms of the map, 0.24 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The peak emission is located at  $v_{LSR} = -19.74$  km s<sup>-1</sup> at ( $\Delta \alpha, \Delta \beta$ ) = (+2", 0"), with a flux density of 5.04 Jy beam<sup>-1</sup>. The dotted straight lines mark the directions of possible outflow arms. The velocity, in km s<sup>-1</sup>, of each map is indicated in the upper left corner of each panel. (A color version of this figure is available in the online journal.)

 Table 2

 Physical Parameters of the Main CO (1–0) Outflows Found around IRAS 05327+3404

Outflow	$R_{\rm max}^{a}$ (pc)	$V_{\max}^{b}$ (km s <sup>-1</sup> )	area <sup>c</sup> (arcsec <sup>2</sup> )	<i>S</i> <sub>ν</sub> (Jy)	$\frac{N_{\rm CO}^{\rm d}}{({\rm cm}^{-2})}$	$M_{\rm out}^{\rm e}$ $(M_{\odot})$	$t_d^{\rm f}$ (10 <sup>4</sup> yr)	$\dot{M}_{\rm out}^{\rm g}$ $(M_{\odot} {\rm yr}^{-1})$	$\frac{P_{\rm out}{}^{\rm h}}{(M_{\odot}~{\rm km~s^{-1}})}$	$F_{\text{out}}^{i}$ $(M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1})$	$L_{\rm out}^{\rm j}$ $(L_{\odot})$
E-W red	0.19	5.8	416	9.90	$1.6  imes 10^{16}$	0.130	3.1	$4.2 \times 10^{-6}$	0.76	$2.4 \times 10^{-5}$	$2.3 \times 10^{-2}$
E-W blue	0.15	4.1	592	13.7	$9.9  imes 10^{15}$	0.117	3.6	$3.2 \times 10^{-6}$	0.48	$1.3 \times 10^{-5}$	$8.4 \times 10^{-3}$
NE red	0.24	3.6	380	6.75	$6.5  imes 10^{15}$	0.049	6.7	$7.3 \times 10^{-7}$	0.17	$2.6  imes 10^{-6}$	$1.4 \times 10^{-3}$

### Notes.

<sup>a</sup> Projected maximum size of the outflow at the  $3\sigma$  contour, adopting a distance D = 1.2 kpc.

<sup>b</sup> Maximum relative velocity of the outflow, either redshifted or blueshifted, with respect to the systemic velocity.

<sup>c</sup> Area in the sky inside the  $3\sigma$  contour of the integrated intensity maps over which the flux is measured.

<sup>d</sup> CO column density, calculated assuming local thermodynamical equilibrium (LTE) conditions.

<sup>e</sup> Mass traced by the outflow, calculated from  $M_{out}[M_{\odot}] = \bar{\mu}m_{\rm H}\Omega_{\rm S}D^2N_{\rm CO}/X[{\rm CO}]$ , where  $\bar{\mu}$  is the average molecular weight, 2.33,  $m_{\rm H}$  is the atomic hydrogen mass,  $\Omega_{\rm S}$  is the solid angle of the source, D is the distance to the source, and  $X[{\rm CO}]$  is the adopted CO abundance relative to H<sub>2</sub>. We used  $X[{\rm CO}] = 10^{-4}$  following Frerking et al. (1982).

<sup>f</sup> Dynamical timescale of the outflow,  $t_d = R_{\text{max}} / V_{\text{max}}$ .

<sup>g</sup> Mass outflow rate,  $\dot{M}_{out} = M_{out}/t_d$ .

<sup>h</sup> Momentum of the outflow,  $P_{\text{out}} = M_{\text{out}} V_{\text{max}}$ .

<sup>i</sup> Momentum flux,  $F_{\text{out}} = P_{\text{out}}/t_d$ .

<sup>j</sup> Outflow mechanical luminosity,  $L_{out} = 0.5 M_{out} V_{max}^3 / R_{max}$ .



Figure 10. (a) Map overlapping the integrated emission of the redshifted (from -20.63 to -15.80 km s<sup>-1</sup>) and blueshifted (from -26.22 to -22.66 km s<sup>-1</sup>) channels of the CO (1–0) line in IRAS 05327+3404. The lowest contour is 0.525 Jy beam<sup>-1</sup> with increments of 0.35 Jy beam<sup>-1</sup>. (b) Map overlapping the higher relative velocity emission of the redshifted and blueshifted channels from -18.34 to -15.80 km s<sup>-1</sup> and from -26.72 to -24.95 km s<sup>-1</sup>, respectively. The first contour is at 0.480 Jy beam<sup>-1</sup>, with increments of 0.32 Jy beam<sup>-1</sup>. (c) Same as panel (b), but overlapping the lower relative velocity emission of the redshifted channels from -20.63 to -18.60 km s<sup>-1</sup> and from -24.69 to -22.66 km s<sup>-1</sup>, respectively. The first contour is at 0.750 Jy beam<sup>-1</sup>, with increments of 0.50 Jy beam<sup>-1</sup>.

around the position of SMM 1 and the NE outflow from the position of SMM 2. We present the parameters of the redshifted and blueshifted arms of the east–west outflow, and the parameters of the redshifted emission of the material that we identified as belonging to the NE outflow.

In order to calculate the mass of each outflow, we measured the flux inside the  $3\sigma$  contour of the integrated intensity maps where we could find emission belonging to each outflow: from -20.63 to -15.81 km s<sup>-1</sup> for the redshifted arm of the E–W outflow, from -25.71 to -22.66 km s<sup>-1</sup> for the blueshifted arm of the E–W outflow, and from -18.09 to -20.63 km s<sup>-1</sup> for the NE outflow. We estimated the CO column densities traced by the redshifted and blueshifted channels adopting  $T_{ex} = 20$  K (Snell et al. 1984; Lada 1985; Aso et al. 2000), assuming local thermodynamical equilibrium conditions and optically thin emission. Given the assumption of optically thin emission, the calculated column density values should be taken as a lower limit to the column density because the lines are probably optically thick. For instance, Bontemps et al. (1996) adopted a mean factor of the opacity correction for the CO line of 3.5, following the detailed study of Cabrit & Bertout (1992). We have also chosen not to use any inclination angle, *i*, for the calculation of



**Figure 11.** Integrated intensity map of the CO (2–1) emission in the velocity range from -25.0 to -13.8 km s<sup>-1</sup>, with a resulting mean velocity of -19.4 km s<sup>-1</sup>. Contours are -3, 3, 6, 9, ... times the rms of the map, 0.19 Jy beam<sup>-1</sup>. The beam size is  $\sim 5''.4 \times 2''.5$ , with P.A. = 88°.8. The triangles mark the positions of the emission peaks in the 261 GHz continuum map (Figure 1(a)).

dynamical timescale, the mass outflow rate, the momentum of the outflow, and the momentum flux. In the case of correcting for the inclination angle, the linear size should be divided by sin *i* and the velocities by cos *i*. Magnier et al. (1996) estimated an inclination angle of  $i = 45^{\circ}$  for the NE outflow, but we do not have any additional information about the orientation of the E–W outflow with respect to the line of sight. Bontemps et al. (1996) estimate a mean correction factor of 2.9, corresponding to a random outflow orientation angle of 57°.3 for the calculation of the CO momentum flux,  $F_{out}$ . Thus, following Bontemps et al. (1996), the corrected momentum flux of the outflows from Table 2 should be  $F_{CO} = 2.9 \times 3.5 \times F_{out} \sim 10 \times F_{out}$ , taking into account the corrections from opacity and the inclination angle mentioned above.

The resulting physical parameters (see Table 2) show that the E–W outflow appears to be more massive by a factor of five, when adding the blueshifted and redshifted arms, than the NE outflow. The dynamical timescale of the outflows is about a few times  $10^4$  yr, but the E–W outflow would have a shorter dynamical timescale by a factor of ~2. The rest of the physical parameters also show that the E–W outflow is a more powerful outflow than the NE outflow.

We compared the momentum flux derived for our outflows with the momentum flux versus radio continuum luminosity correlation of Anglada (1996). We applied to  $F_{out}$  the correction factor of ~10 used by Bontemps et al. (1996). Anglada & Rodríguez (2002) found a radio continuum luminosity of 0.22 mJy kpc<sup>2</sup> for their VLA 2 source. Unfortunately, the VLA observations were not able to resolve this source, but as we discussed in Section 3.1.1, it is safe to assume that all the centimeter emission comes from SMM 1 and that the contribution coming from SMM 2 is much smaller. In this case, we find that the radio continuum luminosity of VLA 2 (SMM 1) falls very well in the correlation with the calculated momentum flux of the E–W outflow. For SMM 2, we can assume a  $3\sigma$  upper



**Figure 12.** Maps of the four-channel average of the CO (2–1) lines in the velocity interval from -29.83 to -11.43 km s<sup>-1</sup>. Contours are 3, 6, 9, ... times the rms of the map, 0.25 Jy beam<sup>-1</sup>. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) emission peaks. The velocity, in km s<sup>-1</sup>, of each map is indicated in the upper left corner of each panel.

limit for its associated radio centimeter continuum luminosity of  $<0.1 \text{ mJy kpc}^2$ . Following the correlation of Anglada (1996), the centimeter luminosity that we would obtain from the momentum flux of the NE outflow would be  $\sim 0.02 \text{ mJy kpc}^2$ , and thus consistent with the VLA upper limit.

We also compared the physical parameters that we derived for our outflows with some of the results of Bontemps et al. (1996). First, we compared the corrected momentum flux of the outflows,  $F_{out}$ , versus the bolometric luminosity,  $L_{bol}$ . We find that the SMM 1 and the E–W outflow lie in the upper right corner of Figure 5 of Bontemps et al. (1996), in the region associated with Class 0 sources, but relatively close to the bestfit correlation found for Class I sources. The location of SMM 2



**Figure 13.** Spectra of the observed  $HCO^+$  (1–0),  $HCO^+$  (3–2), HCN (1–0), CO (1–0), and CO (2–1) lines obtained at four selected points of our maps.

and the NE outflow is more uncertain, but it would be located in the Class I region, close to the best-fit correlation for Class I objects if  $L_{bol} \sim 2-10 L_{\odot}$ . When we compared the momentum flux of the outflows with the mass of the circumstellar envelope derived in Section 4.1 with Figure 6 of Bontemps et al. (1996), we found that SMM 1 is also located in the Class 0 YSOs' region, and close to the best-fit correlation for the Class I sources. On the other hand, SMM 2 and the NE outflow would be close to the region where there is the change from Class 0 to Class I sources.

Finally, we compared our data with the  $F_{out}c/L_{bol}$  versus  $M_{env}/L_{bol}^{0.6}$  plot shown in Figure 7 of Bontemps et al. (1996) that tries to remove luminosity effects from the momentum flux and the envelope mass. The efficiency of our outflows,  $F_{out}c/L_{bol}$ , is ~220–420 for the E–W outflow for SMM1 bolometric luminosities  $L_{bol} \sim 82$ –41  $L_{\odot}$ , and between ~600–125 for the NE outflow for luminosities of SMM 2 ~ 2–10  $L_{\odot}$ . These values place SMM 1 in the region of the youngest Class I sources, and SMM 2 just at the transition between Class 0 and Class I YSOs. The location of SMM 2 is again much more uncertain due to our lack of knowledge about its bolometric luminosity.

We also compared the results we derived from the outflows around IRAS 05327+3404 with the sample of Aso et al. (2000) of CO outflows in Orion. In a similar way, we find that the E–W outflow properties set the submillimeter source in the region occupied by what Aso et al. (2000) called "dark cloud Class 0" objects in the envelope mass versus momentum flux and bolometric luminosity versus momentum flux plots. The location of SMM 2, more difficult to determine, would seem to be more in according with what Aso et al. (2000) called "dark cloud Class I" objects.



**Figure 14.** CO position–velocity cuts along four different position angles: (a) P.A. =  $9^{\circ}$ , (b) P.A. =  $90^{\circ}$ , (c) P.A. =  $141^{\circ}$ , and (d) P.A. =  $65^{\circ}$ . The initial contour is at 1.19 Jy beam<sup>-1</sup>, with increments of 0.79 Jy beam<sup>-1</sup>. The dashed vertical line shows the position of the systemic velocity. The inset map for each figure shows the origin (green square) and the direction of the *P*–*V* cut (green arrow over the red line) over the integrated intensity map of the corresponding transition. The position angle of the *P*–*V* cut is calculated with respect to the N direction. As a reference, positive positions correspond to the NE for P.A. =  $9^{\circ}$  and  $65^{\circ}$ , E for P.A. =  $90^{\circ}$ , and SE for P.A. =  $141^{\circ}$ .



**Figure 15.** Top left column: position–velocity diagrams of the HCN (1–0) line along the directions: (a) P.A. = 90°, (b) P.A. = 140?7, and (c) P.A. = 175°. The initial contour is at 0.30 Jy beam<sup>-1</sup>, with increments of 0.20 Jy beam<sup>-1</sup>. Bottom left column: position–velocity diagrams of the HCO<sup>+</sup> (1–0) line along the directions: (d) P.A. = 90°, (e) P.A. = 140?7, and (f) P.A. = 175°. The initial contour is at 0.42 Jy beam<sup>-1</sup>, with increments of 0.28 Jy beam<sup>-1</sup>. Right column: position–velocity diagrams of the HCO<sup>+</sup> (3–2) line along the directions: (g) P.A. = 44°, (h) P.A. = 104°, (i) P.A. = 135°, and (j) P.A. = 175°. The initial contour is at 0.72 Jy beam<sup>-1</sup>, with increments of 0.72 Jy beam<sup>-1</sup>. The inset maps follow the same conventions as in Figure 14.

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

### 4.3. Kinematic Structures Traced by HCO<sup>+</sup> and HCN

Figure 15 shows the position–velocity (P-V) cuts made for the HCN (1–0), HCO<sup>+</sup> (1–0), and HCO<sup>+</sup> (3–2) lines along some

of the gas structures found in the integrated intensity maps. We find a velocity gradient in an approximately north–south direction, indicated by a velocity shift from  $\sim -22.4$  to -20.8 km s<sup>-1</sup> for HCN and HCO<sup>+</sup> (1–0) in the *P*–*V* cuts following an almost



**Figure 16.** Maps of the first- (a and c) and second-order (b and d) moments of the HCO<sup>+</sup> (1–0) (a and b) and (3–2) (c and d) emission overlaid with the corresponding integrated intensity map in IRAS 05327+3404. The triangles mark the positions of the continuum sources SMM 1 and SMM 2. (A color version of this figure is available in the online journal.)

N–S direction, P.A. =  $175^{\circ}$  (Figures 15(c) and (f)). This velocity shift is also seen along the line connecting the two peaks in the integrated emission maps, P.A. =  $140^{\circ}$ ? (Figures 15(b) and (e)), but with a shallower gradient. The first-order moment map of the HCO<sup>+</sup> (1-0) line (Figure 16(a)) clearly shows this velocity gradient as a transition from redshifted to blueshifted velocities in an approximately north-south direction. The P-V cuts done for the  $HCO^+$  (3–2) line show similar results, but in this case, the extension is considerably reduced: Figures 15(i) and (j) show the two condensations found in the integrated intensity maps and again the larger gradient is found for P.A.  $\simeq 175^{\circ}$  (Figure 15(j)). The first-order moment map of the HCO<sup>+</sup> (3–2) emission (Figure 16(c)) also shows the approximately north-south gradient found in HCO<sup>+</sup> (1–0) (Figure 16(a)), but there is also a change in velocity east to southwest of SMM 1, that was not so clearly seen in the (1–0) line.

The *P*-*V* cut taken in an SW–NE direction along the major axis of the NW condensation for the HCO<sup>+</sup> (3–2) line (Figure 15(g)) recovers the gradient shown in the HCO<sup>+</sup> (3–2) channel maps from  $\sim$ -22.5 to  $\sim$ -21 km s<sup>-1</sup> (Figure 3). This *P*-*V* map shows a main condensation at a velocity  $\sim$ -21.7 km s<sup>-1</sup>, corresponding to the HCO<sup>+</sup> (3–2) NW peak, and two emission plateaus that trace other structures. The first one is located  $\sim$ 5 arcsec to the NE at  $\sim$ -21.1 km s<sup>-1</sup> and it is also found in the *P*-*V* cut with P.A. = 175° (Figure 15(j)). The second one is located  $\sim$ 4 arcsec to the SW, at  $\sim$ -22.3 km s<sup>-1</sup>, is also found in the *P*-*V* cut connecting SMM 1 and SMM 2 (P.A.  $\simeq$  104°), and would correspond to SMM 2 (Figure 15(h)).

The HCO<sup>+</sup> (3–2) P-V cuts show much more clearly a line broadening of  $\sim 2 \text{ km s}^{-1}$  at a position of  $\sim 2-3$  arcsec east of the main HCO<sup>+</sup> emission peak. This is close to the position of the main CO (1–0) peak and the broadening could indicate the presence of some shocks at this position, but it could also be related to rotation or even collapse. This effect is outstanding in the second-order maps of the HCO<sup>+</sup> lines (Figures 16(b) and (d)). HCO<sup>+</sup> line widths are ~0.4–0.6 km s<sup>-1</sup> for most of the map except for a region 6 arcsec in size east of SMM 1. The HCO<sup>+</sup> (3–2) spectra on this part of the map show a complex structure, with shoulders on the line wings and maybe more than one component. Line widths can be as wide as 2.9 km s<sup>-1</sup>. If the line widths corresponded to a rotational flow, we estimate, following Lada (1985), that we would need a mass  $M > 8 M_{\odot}$  interior to the flow to support it, or ~25  $M_{\odot}$  to have a bound self-gravitating structure, which is several times larger than the mass traced by the dust continuum. Therefore, the gas traced by HCO<sup>+</sup> close to SMM 1 is probably gas affected by the local outflows. We do not find any HCO<sup>+</sup> line broadening in the parts of the map to the north where there is redshifted HCO<sup>+</sup> emission.

Finally, the P-V cuts along a direction with P.A.  $\simeq 175^{\circ}$  of the HCO<sup>+</sup> and HCN lines (Figures 15(c), (f), and (j)) also find traces of weak emission  $\sim 10$  arcsec south of SMM 1, which would correspond to the very weak condensation found in the respective channel maps. We also find weak emission  $\sim 20$  arcsec east of the central position of the map in the P-V cuts made in an E–W direction, P.A. = 90°, through the position of the HCO<sup>+</sup> peak (Figures 15(d) and (a)). This would correspond to the weak emission found in HCO<sup>+</sup> (1–0) coinciding with a local peak of CO (1–0). It is unclear what is the nature of these objects, probably gas in some stage of pre-stellar core or other clumpiness of the cloud.

#### 4.4. The Distribution of the Molecular Gas

Figure 17 shows the superposition of the integrated intensity maps of the CO, HCO<sup>+</sup>, and HCN emissions obtained from the BIMA observation, mainly showing the gas distribution at larger scales. Figure 18 shows a similar map zoomed in at smaller scales in order to compare the BIMA and SMA observations.



**Figure 17.** Integrated intensity emission of the CO (1–0) (red contours), HCO<sup>+</sup> (1–0) (blue contours), and HCN (1–0) (gray scale and one black contour at FWHM) emission in the velocity intervals -27.47 to -15.04 km s<sup>-1</sup>, -22.42 to -20.78 km s<sup>-1</sup>, and -22.15 to -21.15 km s<sup>-1</sup>, respectively. The triangles mark the positions of the continuum peaks and the squares mark the positions of the HCO<sup>+</sup> (3–2) peaks.

The bulk of the more intense HCN and HCO<sup>+</sup> emission, which will trace the denser component of the molecular gas, is found in a central region,  $\sim 20 \times 15$  arcsec in size, and it encompasses the submm continuum emission and the two SMM sources, SMM 1 and 2. Lower density gas probably surrounds this central region, as it is traced by the weak HCO<sup>+</sup> (1–0) component. The CO lines seem to trace mostly the molecular outflows.

The molecular emission peaks show a large degree of coincidence among them and with the positions of the SMM sources: two of the HCO<sup>+</sup> peaks coincide with the SMM sources, while the third one (the one we named NW HCO<sup>+</sup>) also coincides with the northern HCN plateau. Only the HCN emission peak seems to be located in between SMM 1 and SMM 2. Thus, the molecular and continuum data show that there are multiple objects in the region. Two of these objects are probably protostars because of the detected submm emission and its alignment with some of the high-velocity structures found in CO. The third condensation, only found in the HCO<sup>+</sup> and HCN lines, is either a starless or pre-stellar core, too cold to show a submillimeter peak.

There are other minor emission peaks in our maps: a local CO (1–0) emission peak that coincides with a  $6\sigma$  peak of the HCO<sup>+</sup> (1–0) line at ~18 arcsec east of IRAS 05327+3404, and the hint of another possible condensation seen in the channel maps of HCO<sup>+</sup> (1–0) and (3–2) located ~10 arcsec S of SMM 1.

## 4.4.1. The Missing CO Emission

There are probably different reasons to explain the big difference between CO and the other molecules, and why it is concentrated in a relatively E–W strip. CO traces lower density material than HCO<sup>+</sup> and HCN, and thus CO emission should be more widespread over the region. This makes it more likely to suffer from missing flux effects. From the low-intensity distribution of the HCO<sup>+</sup> (1–0) emission, we would



**Figure 18.** Integrated intensity emission of the HCO<sup>+</sup> (3–2) line (thick black contours) overlaid over the integrated intensity of the CO (2–1) line (thick red contours), the integrated intensity map of HCO<sup>+</sup> (1–0) (gray scale), the integrated intensity map of HCN (1–0) (dashed blue contours), and the integrated intensity map of CO (1–0) (dotted red contours). The triangles mark the positions of the continuum peaks SMM 1 and SMM 2, and the squares mark the positions of the HCO<sup>+</sup> (3–2) peaks.

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

expect that CO would be distributed all around the molecular core, but most of the emission is probably filtered out by the interferometer. The integrated intensity map of CO mainly traces high-velocity gas (Figure 9), which we expect would suffer less from filtering-out by the interferometer as it would be relatively more compact, and most of the CO emission we observe is probably due to molecular outflow emission. As a consequence (see Section 3.2.4), we do not find CO (1–0) emission around the systemic velocities almost anywhere in our map. This prevents any chance of disentangling the relationship between the high-velocity and "quiescent" CO gas in the region.

We took several spectra along the east–west direction on both sides of the CO integrated intensity maximum (Figure 19), in order to study the missing CO emission. The line emission in the spectra moves from mostly blueshifted to the west of the emission peak (spectra "a" and "b") to mostly redshifted to the east (spectra "f" and "g"), with a gradual decrease of blueshifted emission and an increase of redshifted emission from the "c" to the "e" spectra. All these spectra show missing CO emission around the systemic velocities ( $-21.7 \text{ km s}^{-1}$ ), where we find what seems to be a more or less deep absorption feature in most of them. Only the farthest positions, "a" and "i," might not show this absorption feature.

The spectral data could be indicating that there is an extended foreground, and colder, gas component surrounding the core revealed by  $HCO^+$  and HCN, which is responsible for absorbing the CO emission. However, this absorption feature should also be apparent in single-dish observations, but that is not the case for the spectra of the CO (2–1) line of Magnier et al. (1996). Thus, we conclude that the interferometers mostly detect the CO components related to the outflows (relatively more compact and less subject to filtering out).



Figure 19. CO spectra, in units of Jy beam<sup>-1</sup>, taken at nine different positions on both sides of the CO (1–0) emission peak of IRAS 05327+3404. The offset positions are referenced to the nominal position of IRAS 05327+3404.

# 4.5. The Structure of the Region and the Nature of the Powering Sources

The millimetric and submillimetric observations show that the properties and the structure of the gas around the position of IRAS 05327+3404 "Holoea" are much more complicated than previously thought.

The data are helpful in the description of the morphology and the identification of existing protostellar objects, allow us to characterize several molecular outflows, and argue for an identification of the respective powering sources. Nonetheless, our data cannot give any conclusive determination for several other velocity structures found in the region, and the possibility that there exist more embedded sources is still open.

Magnier et al. (1996) discussed three possible toy models that could describe the physical structure of M36 "Holoea." They favored a scenario in between two of those models, in which there would be a molecular outflow powered by the star, with the redshifted gas not moving in a well-collimated jet, but it would be spraying in a wide range of directions, or the presence of a thick disk around the star, IRAS 05327+3404, would shadow the south-pointing jet and outflow and we would only see the south-side emission far from the star and at lower velocities. They also discussed the possibility that the system could be a binary (Magnier et al. 1999b) in order to explain some of the properties of the observed SED. From the results of our data, we favor a different interpretation of the structure of the region.

Our continuum data show that there are two submillimetric sources in the region, SMM 1 and SMM 2, separated by  $\sim$ 6 arcsec ( $\sim$ 7300 AU), which would be powering the two main outflows we identify in the CO (1–0) observations: SMM 1

would be powering the east–west bipolar outflow, while SMM 2 would be the powering source of the NE redshifted outflow. The orientation of both outflows would be different with respect to the line of sight, undetermined for the E–W outflow, while the NE outflow could have an inclination angle,  $i = 45^{\circ}$  (Magnier et al. 1999b). The blueshifted counterpart of the NE outflow is not visible, maybe because its emission is confused with the blueshifted lobe of the E–W outflow. Our data are not good enough to distinguish that, although this last possibility seems to be unlikely.

The gas surrounding the two SMM objects would have masses from a few tenths of solar masses (~0.8  $M_{\odot}$  for SMM 2) up to 1–2  $M_{\odot}$  (~1.5  $M_{\odot}$  for SMM 1). Additionally, the HCO<sup>+</sup> (1-0), HCO<sup>+</sup> (3-2), and HCN (1-0) lines also have emission peaks approximately coinciding with these two objects, which confirms that the SMM sources are associated with dense gas. The comparison we have been able to do between the  $L_{\rm bol}$ measured by Magnier et al. (1996), the envelope masses and the outflow parameters we derived for our objects, allows us to guess an evolutionary stage for both SMM sources. SMM 1 would be in a Class 0, probably very early Class I, stage as indicated by the outflow parameters and the relationship between the bolometric luminosity and the envelope mass. SMM 2 seems to be in a more advanced stage of evolution, advanced Class I probably, given the weaker molecular outflow and its outflow parameters. Additionally, SMM 1 seems to be related to a denser gas, traced by the continuum and high-density tracers, while SMM 2 seems to be in a slightly less dense environment. This also supports the earlier evolutionary stage for SMM 1. Thus, we think that our data rather shows that the two SMM sources are in an earlier evolutionary stage than previously expected, probably early Class I stage. We must be cautious though given the uncertainties related to the calculation of the outflow parameters, the difficulties in the determination of the bolometric luminosity of each object, and the general complex kinematic structure of the region.

There should be another object located close to the two SMM sources,  $\sim$ 8.5 arcsec NW of SMM 2 (see Section 3.2.1), as detected by the HCO<sup>+</sup> and HCN lines. This object is not detected in the continuum, which suggests that it is probably a pre-stellar core or some cold embedded object. Interestingly, this core is also aligned with the direction of the NE outflow, but the lack of continuum emission associated with this object would a priori preclude it to be considered a candidate to be the powering source of any outflow. Additionally, there are two other condensations visible in some of the HCO<sup>+</sup>, HCN, and CO data, but not associated with continuum emission: one is located  $\sim 18$  arcsec east of SMM 1 and the other  $\sim 10$  arcsec south of SMM 1. With the limited amount of information that we have, these two condensations seem to be just two candidate starless cores.

Magnier et al. (1999b) proposed that the system they found could be a binary, which is a possibility given the short projected distance between the SMM sources. Additionally, we also found a velocity gradient in the N-S direction, at a scale of  $\sim 40$  arcsec, and another gradient in the gas around the NW HCO<sup>+</sup> position. These gradients suggest some internal motions, but there does not seem to be any significant relative motion between SMM 1 and SMM 2.

## 5. CONCLUSIONS

We observed the object named "Holoea," associated with the IRAS 05327+3404 source in M36, with the SMA telescope at 1.1 mm using the CO (2-1) and HCO<sup>+</sup> (3-2) lines, and with the BIMA telescope at 3 mm using the CO (1-0), HCO<sup>+</sup> (1-0), and HCN (1-0) lines. This object had been identified by Magnier et al. (1996, 1999b) as a candidate transitional YSO between Class I and Class II with several unusual properties. We detected the emission of the three molecules, but they show a markedly different distribution. We also detected dust continuum emission at 1.1 mm in the SMA observations.

The continuum emission reveals two submillimeter peaks. The more intense one, SMM 1, with a flux density of 39.1 mJy, coincides within uncertainties with the nominal position of IRAS 05327+3404 and with the VLA 2 source of Anglada & Rodríguez (2002), and we identify it as the submillimeter counterpart of the IRAS source. The second submillimeter emission peak, SMM 2, with a flux density of 19.9 mJy, is located ~6 arcsec to the NW of SMM 1. From the dust emission, we calculated a mass of  $1.5 M_{\odot}$  for SMM 1 and a mass of 0.8  $M_{\odot}$  for SMM 2.

The distribution of the  $HCO^+$  (1–0), (3–2), and HCN (1–0) emissions is more centrally concentrated, as is expected for these molecular tracers, and they show at least two emission peaks. The main emission peak of the HCO<sup>+</sup> lines is found around the position of SMM 1, another HCO<sup>+</sup> (3–2) emission peak coincides with SMM 2, and there is a third peak, located 8.5 arcsec to the NW of SMM 1, not found in the continuum data, which is also present in the HCO<sup>+</sup> and HCN data. Thus, there is evidence of at least two protostellar objects and a third possible pre-stellar condensation. The integrated CO (1-0) emission is mainly found in an E-W direction, with the intensity peak  $\sim$ 3 arcsec east of the position of SMM 1. The CO lines around the central position show a dip in the intensity, which we attribute to the filtering out of extended emission by the interferometers.

We found several different velocity components in the redshifted and blueshifted channels of the molecular lines. We identify two main molecular outflows in the region: a bipolar CO outflow elongated in an E-W direction with the blueshifted and redshifted lobes overlapping over the position of SMM 1, which was also detected at lower angular resolution by Magnier et al. (1999b); and an outflow in the NE direction (P.A. =  $9^{\circ}$ ), only found at redshifted velocities, pointing to the position of SMM 2, in approximately the same direction as the outflow detected by Magnier et al. (1999b). We identify SMM 1 as the best candidate to be the powering source of the E-W outflow, while SMM 2 could be the powering source of the NE outflow and the embedded YSO proposed by Magnier et al. (1999b). We find other high-velocity structures around the central part of the map, and evidence of line broadening due to shocks and/or outflows in the CO and HCO<sup>+</sup> spectra, that might point to the presence of a third outflow or simply to the interaction of the E-W outflow with the surrounding gas. The sensitivity and angular resolution of our data do not allow us to avoid the confusion in the region.

From the determination of the physical parameters of the two molecular outflows and the SMM objects, we have also been able to look into the evolutionary stage of the YSOs. We propose that SMM 1 is in an earlier evolutionary stage than SMM 2, and probably in an early Class I phase. SMM 2 seems to be in a more advanced stage of the Class I phase, but probably not by much.

The general picture that we propose for the region is that it is a more complex system than it was thought, with at least two YSOs, which are powering the two main outflows detected in our CO channel maps. There could be more objects in the region, and additional outflows, but the detailed structure is very difficult to disentangle with the data available to us. Most of these objects are probably embedded, except "Holoea," which is beginning to be revealed, probably by the progressive clearing of the gas by one (or several) of the detected molecular outflows. Further multi-wavelength (optical, NIR, submillimetric) observations are needed to obtain a more precise description of the structure of the objects and of the physical processes that are taking part in them.

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Facilities: BIMA, SMA

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