L1448 IRS2E: A CANDIDATE FIRST HYDROSTATIC CORE

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ABSTRACT

Intermediate between the prestellar and Class 0 protostellar phases, the first core is a quasi-equilibrium hydrostatic object with a short lifetime and an extremely low luminosity. Recent magnetohydrodynamic (MHD) simulations suggest that the first core can even drive a molecular outflow before the formation of the second core (i.e., protostar). Using the Submillimeter Array and the Spitzer Space Telescope, we present high angular resolution observations toward the embedded dense core IRS2E in L1448. We find that source L1448 IRS2E is not visible in the sensitive Spitzer infrared images (at wavelengths from 3.6 to 70 μm) and has weak (sub-) millimeter dust continuum emission. Consequently, this source has an extremely low bolometric luminosity (<0.1 L⊙). Infrared and (sub-) millimeter observations clearly show an outflow emanating from this source; L1448 IRS2E represents thus far the lowest luminosity source known to be driving a molecular outflow. Comparisons with prestellar cores and Class 0 protostars suggest that L1448 IRS2E is more evolved than prestellar cores but less evolved than Class 0 protostars, i.e., at a stage intermediate between prestellar cores and Class 0 protostars. All these results are consistent with the theoretical predictions of the radiative/MHD simulations, making L1448 IRS2E the most promising candidate of the first hydrostatic core revealed so far.

Key words: ISM: clouds – ISM: individual objects (L1448, L1448IRS2, L1448IRS2E) – ISM: jets and outflows – stars: formation

Online-only material: color figures

1. INTRODUCTION

Stars form by the gravitational collapse of dense cores in molecular clouds. A comprehensive understanding of the formation and evolution of dense cores is thus a necessary prerequisite to the understanding of the origin of stellar masses, multiple systems, and outflows. Over the past decade, observational studies of (low-mass) dense cores have made significant progress (see, e.g., Reipurth et al. 2007 for recent reviews). Representing the earliest phase of star formation, both prestellar and protostellar cores have been extensively observed and studied using large (sub-) millimeter telescopes (e.g., James Clerk Maxwell telescope (JCMT) and IRAM 30 m) and infrared telescopes (e.g., Spitzer Space Telescope). In practice, however, it is still difficult to distinguish the two types of cores because of the lack of readily observable differences between them. This is illustrated by the fact that several “prestellar” cores, like L1014, were found to harbor very low luminosity protostars in sensitive Spitzer observations (see Young et al. 2004). Consequently, despite all of the observational advances in the past decade, we still do not have a good understanding of the evolutionary process that turns a prestellar core into a protostar.

On the theoretical side, the collapse and evolution from prestellar cores to Class 0 protostars have been long studied since the pioneering work of Larson (1969). Theoretical calculations and simulations in fact predict two successive collapse phases, before and after the dissociation of molecular hydrogen, resulting in two different hydrostatic objects (see, e.g., Larson 1969; Masunaga et al. 1998; Masunaga & Inutsuka 2000; André et al. 2009). The collapsing prestellar core is initially optically thin to the thermal emission from dust grains, and the compressional heating rate by the collapse is much smaller than the cooling rate by the thermal radiation. The collapse is therefore isothermal at the very beginning. This condition is broken when the compressional heating rate surpasses the radiative cooling rate, and the central temperature increases gradually above 10 K. The collapse is then decelerated and forms a shock at the surface of a quasi-adiabatic hydrostatic object, the so-called first hydrostatic core or first core, which consists mainly of hydrogen molecules. The inward motion at this phase is called the “first collapse.” When the central temperature reaches about 2000 K, hydrogen molecules begin to dissociate into atoms, which acts as an efficient coolant of the gas. When released gravitational energy is consumed by the dissociation, the gas pressure cannot increase rapidly enough to support the first core against its self-gravity, the “second collapse” begins. After the dissociation is completed, the “second core,” a truly hydrostatic protostellar object, forms in the center. Most, if not all, Class 0 protostars observed so far actually belong to the population of the “second cores” (Ph. André 2009, private communication).

Intermediate between the prestellar and Class 0 protostellar phases, the first core is a transient object accreting from the surrounding dense envelope; the lifetime of the first core is calculated to be only 103–104 yr (Boss & Yorke 1995; Masunaga et al. 1998; Machida et al. 2008). Based on radiative hydrodynamic (RHD) simulations, Boss & Yorke (1995) and Masunaga et al. (1998) modeled the spectral energy distribution (SED) of the first core and found that it should have an extremely low bolometric luminosity (<0.1 L⊙) and have no detectable infrared emission at wavelengths shorter than ~30 μm with current telescopes. Furthermore, recent magnetohydrodynamic (MHD) simulations have found that the first core can even drive a molecular outflow before the formation of the second core (i.e., protostar; Tomisaka 2002; Banerjee & Pudritz 2006; Machida...
et al. 2008). Therefore, the observational detection of the first core would not only confirm the predictions of RHD models but also set strong constraints on MHD models of protostellar outflows. Unfortunately, due to its short lifetime and extremely low luminosity, no first core has been observationally found as yet.

In this paper, we present Submillimeter Array (SMA; Ho et al. 2004) and Spitzer Space Telescope (Spitzer) observations toward an embedded dense core in the L1448 region \( (d = 240 \pm 20 \text{ pc}; \text{Hirota et al. 2008}) \). As a bridge between the isolated star-forming cores and the large-scale clusters, L1448 is an excellent region for studying star formation on the intermediate scale and has been observed extensively in the past two decades (see, e.g., Bally et al. 2008, and reference therein). L1448 IRS2, in the western part of the L1448 filament, was classified as a Class 0 protostar by O’Linger et al. (1999). Located \( \sim 50'' \) to the east of IRS2, another dense core was revealed in the SCUBA submillimeter images in O’Linger et al. (1999) and was formally cataloged as SCUBA core No. 31 in Hatchell et al. (2005) and SMM J032543+30450 in Kirk et al. (2006). This core was found to have a mean kinetic gas temperature of \( T_{\text{kin}} \approx 11 \text{ K} \), and the observed width of \( \text{NH}_3 (1, 1) \) is \( \sim 0.16 \text{ km s}^{-1} \) (Rosolowsky et al. 2008). We refer to this dense core as L1448 IRS2E in this work.

2. OBSERVATIONS AND DATA REDUCTION

2.1. SMA Observations

L1448 IRS2E was observed with the SMA on 2009 December 25 in the compact configuration (seven antennas were used in the array). The digital correlator was set up to cover the frequency ranges 216.9–220.9 GHz and 228.8–232.8 GHz in the lower sideband (LSB) and upper sideband (USB), respectively. The three isotopic CO (2–1) lines and several other lines, e.g., \( \text{N}_2\text{D}^+ (3–2) \) and \( \text{SiO} (5–4) \), were observed simultaneously in this setup. The 1.3 mm dust continuum emission was also recorded with a total bandwidth of \( \sim 7.5 \text{ GHz} \) (\( \sim 3.8 \text{ GHz USB and } \sim 3.7 \text{ GHz LSB} \)). System temperatures ranged from 100 to 150 K (depending on elevation), with a typical value of \( \sim 120 \text{ K} \). Quasar 3c273 was used for bandpass calibration and quasars 3c84 and 0359+509 for gain calibration. 3c273 was also used for absolute flux calibration, from which we estimate a flux accuracy of \( \sim 20\% \), by comparison of the final quasar fluxes with the SMA calibration database. The data were calibrated using the IDL MIR package and imaged using the Miriad toolbox (Sault et al. 1995). The SMA synthesized beam size and theoretical noise levels at 1.3 mm dust continuum and in the \( ^{12}\text{CO} (2–1) \) line, with robust \( \nu \sigma \) weighting 1.0, are \( 3.9 \times 2.6, 0.48 \text{ mJy beam}^{-1} \), and \( \sim 53 \text{ mJy beam}^{-1} \) (channel width \( \sim 1.0 \text{ km s}^{-1} \)), respectively.

2.2. Spitzer Observations

The infrared data for L1448 were obtained from the Spitzer Science Center (SSC) archive. The L1448 dark cloud, which is part of the Perseus molecular cloud, was observed in 2004 as part of the Spitzer Legacy Program “From Molecular Cores to Planet Forming Disks” (c2d; Evans et al. 2003), by both the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer for Spitzer (MIPS). The infrared data were reduced by the c2d team and are publicly available from the SSC science archive. The IRAC and MIPS results of Perseus have been published by Jørgensen et al. (2006) and Rebull et al. (2007), respectively. The details of the observations and data reductions can be found in Dunham et al. (2008).

3. RESULTS

3.1. Infrared, Submillimeter, and Millimeter Continuum Emission

Figure 1 shows the SCUBA 850 \( \mu\text{m} \) dust continuum contours of the L1448 complex (from Kirk et al. 2006; publicly available on the COMPLETE Web site\(^5\)), plotted on the Spitzer images. The SCUBA contours show the arc-shaped filamentary structure of L1448, in which the three well-known Class 0 protostars (i.e., L1448C, IRS3, and IRS2E) are labeled. Located \( \sim 50'' \) to the east of source IRS2, the dense core, referred to as IRS2E, is seen in the SCUBA image. This core is also spatially coincident with a molecular cloud core revealed by IRAM 30 m \( \text{H}_2^+ \) (1–0) observations (X. P. Chen et al. 2010, in preparation) and has a line-of-sight velocity (LSR velocity \( \sim 1 \text{ km s}^{-1} \); Rosolowsky et al. 2008) similar to the other Class 0 protostars, indicating that it is physically associated with the L1448 filament. However, no compact infrared emission was detected from L1448 IRS2E in any of the Spitzer bands (from 3.6 to 70 \( \mu\text{m} \); see Figures 1(a)–(d)), suggesting that this source is extremely cold. We note that the Spitzer data of L1448 were obtained with the c2d legacy program, a large infrared survey toward five nearby large molecular clouds (Chamaeleon II, Lupus, Ophiuchus, Perseus, and Serpens). In the c2d observations, all the known Class 0 protostars in these five clouds were detected (Evans et al. 2009, and references therein), which prove that these images have enough sensitivity to detect the youngest protostars. This indicates that the non-detection of L1448 IRS2E in the Spitzer images is not due to insufficient imaging sensitivity but is observationally significant.

In the SMA 1.3 mm dust continuum images, a weak continuum source (~6σ level; R.A. = 03:25:25.66, decl. = 30:44:56.7, J2000) is found within the IRS2E core (see Figures 1(b)–(d)). This source is evident in images made from visibility data of either sideband as well as in both halves of the track, suggesting that it is not an artifact in the data. Interestingly, the IRAC images (at all four bands) show a diffuse jet-like feature to the south of IRS2E, with this SMA dust continuum source located at the apex (see Figures 1(a) and (b)). From Gaussian fitting in the cleaned-restored images, we derive a flux density of \( 6 \pm 2 \text{ mJy} \) for this dust continuum source. Assuming that the 1.3 mm dust continuum emission is optically thin, the total gas mass (\( M_{\text{gas}} \)) of IRS2E is calculated with the same method described in Luhman & Henning (1997). In the calculations, we adopt a dust opacity of \( \kappa_d = 0.5 \text{ cm}^2 \text{ g}^{-1} \), which is a typical value for cold and dense cores with an average number density of \( n(\text{H}_2) = 10^5 \text{ cm}^{-3} \) (Ossenkopf & Henning 1994), and a dust temperature of \( \sim 11 \text{ K} \), which is similar to the kinetic gas temperature of L1448 IRS2E. The total gas mass of this source, estimated from the SMA dust continuum observations, is \( \sim 0.04 \pm 0.01 \text{ M}_\odot \).

To further estimate the submillimeter and millimeter fluxes, in Figure 2 we show the SCUBA 450 \( \mu\text{m} \), 850 \( \mu\text{m} \), and Bolocam 1.1 mm images of L1448 IRS2, taken from the JCMT science

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\(^5\) http://www.cfa.harvard.edu/COMPLETE
Figure 1. (a) Spitzer IRAC band 3 (5.8 μm) image of the L1448 complex overlaid with JCMT/SCUBA 850 μm dust continuum contours. The SCUBA 850 μm dust continuum contours levels correspond to 3, 5, 8, 12, 15, and 20σ, where 1σ level is ∼40 mJy beam⁻¹. White dashed arrows show the directions of the jets driven by IRS1 and IRS2, respectively (see also Davis et al. 2008). (b) The SMA 1.3 mm dust continuum contours (green) of L1448 IRS2 plotted on the Spitzer IRAC 8.0 μm image. The SMA contours start at ∼3σ (1σ ∼ 0.85 mJy beam⁻¹) with steps of ∼1σ. The synthesized SMA beam is shown as a green oval in the bottom left corner. (c) The same as in (b), but plotted on the Spitzer MIPS 24 μm image. (d) The same as in (b), but for Spitzer MIPS 70 μm image. (A color version of this figure is available in the online journal.)

archive⁶ and Enoch et al. (2006), respectively. As shown in Figure 2, the submillimeter continuum emission from source IRS2E shows a roughly centrally peaked condensation separated from the IRS2 core, while the 1.1 mm continuum emission from IRS2E is weak and elongated, and no core was identified at this position by Enoch et al. (2006). The fluxes within one beam around the SMA continuum source are estimated to be ∼1200 mJy at 450 μm, ∼400 mJy at 850 μm, and ∼300 mJy at 1.1 mm, respectively (see Figure 2 and Table 1). However, it must be noted that the peak positions of the IRS2E core in the SCUBA 450 μm, 850 μm, and SMA 1.3 mm images are different from each other (∼10″ offset). It appears that the single-dish data reveal the entire (extended) low-mass dense core, while the SMA data show a faint compact source which is embedded in this core, but not at its center. Deeper (sub-) millimeter dust continuum observations are needed to investigate the position and density structure of this core.

Figures 3 shows the velocity channel maps of the SMA 12CO (2–1) emission of L1448 IRS2E. For comparison, the SMA 12CO (2–1) emission from L1448 IRS2 is also plotted here (the SMA data of IRS2 were taken from H. G. Arce et al. 2010, in preparation). For IRS2E, CO emission is detected to the south of the SMA continuum peak at velocities from V_LSR = ∼7 to ∼30 km s⁻¹, with the cloud systemic velocity being ∼4.1 km s⁻¹. This redshifted CO emission exhibits an elongated and narrow structure. No blueshifted CO emission was detected around IRS2E in the SMA observations, even though the SMA primary beam of ∼55″ (at 230 GHz) covers the area where we would expect to see the blueshifted lobe if it were there. Hatchell et al. (2007) observed the L1448 region in the CO (3–2) line using the JCMT, and similar to our findings, they detected no blueshifted emission around L1448 IRS2E.

³Because the 850 μm fluxes in Kirk et al. (2006, 2007) are somewhat uncertain (due to issues with the calibration), we prefer using the original SCUBA images of L1448 IRS2 (from the JCMT science archive) to estimate the submillimeter fluxes of L1448 IRS2E.
As shown in Figure 3, several elongated CO lobes are seen around IRS2E in the velocity channels from $\sim 7$ to $\sim 13$ km s$^{-1}$, which come from the redshifted outflow driven by L1448 IRS2. The Class 0 protostar IRS2 was first proposed to be a binary system by Wolf-Chase et al. (2000) based on the NRAO 12 m CO (1–0) observations that mapped two distinct outflows from IRS2. Volgenau et al. (2002) claimed the detection of a binary system in IRS2 using BIMA, but no results (e.g., spatial separation and image) are reported as yet. Other studies (e.g., Tobin et al. 2007) have referenced Volgenau et al. (2002) and Volgenau (2004) as stating that IRS2 is part of a binary system with a companion with about 10$''$ to the northwest. We would have expected to detect this presumed companion in our SMA images, which have a synthesized beam of $\sim 3''$ (see Figure 4), but we do not see evidence in our SMA dust continuum maps. Moreover, we do not find any evidence of this presumed companion in the IRAC and MIPS images, nor is it detected in the 450 $\mu$m SCUBA map (with an $\sim 8''$
beam, see Figure 2). We therefore consider IRS2 as a single source here. In fact, the structures of the outflow from IRS2 can be explained without the need to invoke the unseen binary companion (see Figures 3 and 4). Most of the structures seen at redshifted velocities appear to delineate the walls of the 50° wide outflow cavities, while the elongated redshifted emission along the outflow axis most probably traces the dense collimated part of the outflow, as seen in other sources (e.g., Santiago-García et al. 2009) and predicted by so-called unified outflow model (e.g., Shang et al. 2007; see Figure 4). More details about the IRS2 outflow will be presented in another paper (H. G. Arce et al. 2010, in preparation).

Figure 4 shows the velocity-integrated intensity map of the SMA 12CO (2–1) emission of L1448 IRS2E and IRS2. To the south of IRS2E, the collimated redshifted CO lobe (~40° or 9600 AU in length) is spatially coincident with the infrared jet detected in the Spitzer IRAC images and the CO (3–2) red emission detected at the JCMT. The orientation and morphology of this CO lobe suggest that it is neither part of the cavity wall of the IRS2 extended outflow nor part of the molecular jet from IRS2. These results indicate that L1448 IRS2E, a cold core with no detectable infrared emission, is driving a molecular outflow. Nevertheless, further observations, e.g., short-spacing data, are needed to recover the missing flux of extended structure and to improve the quality of the outflow maps.

Assuming that the 12CO (2–1) line emission is optically thin, the outflow mass of L1448 IRS2E is derived with the standard manner (e.g., Cabrit & Bertout 1990). In the calculations, we assume LTE conditions and an excitation temperature of 20 K (the values in the range of 10–50 K modify the calculations by less than a factor of 2). The derived outflow mass of IRS2E is about 2 × 10^{-3} M_⊙. For other properties relying on a knowledge of the outflow velocity (i.e., age \(t_{\text{flow}}\), momentum \(P\), energy \(E\), force \(F_m\), and mechanical luminosity \(L_m\)), we adopt a value of 25 km s^{-1}, where we assume that the outflowing gas is moving at the maximum observed velocity. We obtain \(t_{\text{flow}} \sim 1800\) yr (assuming a lobe size of 9600 AU), \(P \sim 0.05\) M_⊙ km s^{-1}, \(E \sim 1.2 \times 10^{43}\) erg, \(F_m \sim 2.5 \times 10^{-5}\) M_⊙ km s^{-1} yr^{-1}, and \(L_m \sim 0.05\) L_⊙, without correcting for the unknown inclination of the outflow with respect to the plane of the sky. The outflow mass-loss rate \(M_{\text{out}}\), estimated directly from the mass and age \(t_{\text{flow}}\), is \(\sim 1.0 \times 10^{-6}\) M_⊙ yr^{-1}. We note that all these outflow parameters refer only to the compact outflows detected in the SMA maps and thus represent lower limits.

4. DISCUSSION

4.1. Spectral Energy Distribution

Table 1 lists the (sub-) millimeter fluxes of L1448 IRS2E, estimated from the SCUBA, Bolocam, and SMA images. Since there is no local emission peak at the position of the SMA compact source in the SCUBA/Bolocam images (see Figure 2), the estimated fluxes per beam around IRS2E in these images represent conservative upper limits to the fluxes from the embedded source. The 3σ upper limits in the Spitzer images are also listed in Table 1. Based on these data points, we constructed the SED of IRS2E (plot not shown here). To estimate the luminosity of IRS2E, we first interpolated and then integrated the SED (all the upper limits were used), always assuming spherical symmetry. Interpolation between the flux densities was done by a \(\chi^2\) single-temperature graybody fit to all points.
at $\lambda \geq 70$ $\mu$m, using the same method as described in Chen et al. (2008). A simple logarithmic interpolation was performed between all points at $\lambda \leq 70$ $\mu$m. The estimated bolometric luminosity of L1448 IRS2E is less than 0.1 $L_\odot$.

Although only an upper limit to the bolometric luminosity could be derived, we can still use it to further constrain the evolutionary stage of L1448 IRS2E. If we assume a steady mass accretion rate given by $M = 0.975 c_s^2 / G$ (Shu 1977), where $c_s$ is the effective sound speed, for a gas temperature of 10 K the accretion rate is $\sim 2 \times 10^{-6} M_\odot$ yr$^{-1}$. The accretion luminosity is calculated as $L_{\text{acc}} = GMM/R_\ast$, where $M_\ast$ is the stellar mass and $R_\ast$ is the stellar radius. The bolometric luminosity being $<0.1 L_\odot$ implies a protostellar mass of $<0.01 M_\odot$, assuming a radius of 2 $R_\odot$. The age of a $<0.01 M_\odot$ “protostar” under the assumption of a constant mass accretion rate of $2 \times 10^{-6} M_\odot$ yr$^{-1}$ is then calculated to be $<5000$ yr, which is consistent with the outflow age estimated above ($\geq 1800$ yr).

The estimated low luminosity and age suggest that L1448 IRS2E is a very young object, in which star formation has just started. Nevertheless, it must be noted that uncertainties remain in our estimates due to the limited observations available. More information, such as Herschel Space Observatory imaging at 75–300 $\mu$m, is needed to constrain the SED of L1448 IRS2E in order to address more precisely its evolutionary status.

4.2. Comparisons to Prestellar, Class 0, and VeLLO Objects

Comparison to Prestellar Cores. Prestellar cores are dense ($n_\text{H} \sim 10^4–10^6$ cm$^{-3}$) cores which are self-gravitating and evolve toward higher degrees of central condensation, but no central hydrostatic protostellar object exists yet within the core (Andrè et al. 2000, 2009). Although the properties of L1448 IRS2E are still poorly known, its observed narrow width of the NH$_3$ line ($\sim 0.16$ km s$^{-1}$; Rosolowsky et al. 2008), as well as the fact that no point-like source is detected in the Spitzer images, resembles the properties of prestellar cores (see Andrè et al. 2009). However, as suggested by the SMA CO (2–1) observations, L1448 IRS2E appears to drive a molecular outflow, which implies ongoing accretion onto a central condensation and has never seen before in prestellar cores. Furthermore, the estimated ratio of $H^{13}$C/O (Bachiller et al. 2003) to $H_2$CO (Bachiller et al. 2005) in the IRS2E core is $\sim 0.26$, similar to that of “evolved” prestellar cores, like L1544 (see Tafalla et al. 2005), which suggests that the IRS2E core is chemically evolved and probably already passed the last stage of the prestellar phase.

Comparison to Class 0 Objects. Class 0 objects are the youngest accreting protostars with an age of a few $\times 10^4$ yr. These objects are in an early evolutionary stage, right after point mass formation, when most of the mass of the system is still in the surrounding dense core/envelope (Andrè et al. 2000). They represent the truly hydrostatic protostellar objects (i.e., the second core) formed in dense cores. So far at least 50 Class 0 protostars have been identified (Andrè et al. 2000; Froebrich 2005). Most of them are detectable in the Spitzer images (at least in the MIPS bands) and are associated with strong submillimeter and millimeter dust continuum emission (in both single-dish and interferometric maps). Although the collimated outflow from IRS2E possesses the typical properties of an outflow from a Class 0 protostar (see Arce et al. 2007), an obvious difference between L1448 IRS2E and known Class 0 protostars (e.g., L1448C, IRS3, and IRS2) is that IRS2E is not visible in the sensitive Spitzer images, has weak dust continuum emission, and consequently has an extremely low bolometric luminosity ($<0.1 L_\odot$). The estimated age of L1448 IRS2E (a few $\times 10^4$ yr) is also much less than those of the Class 0 protostars, suggesting that IRS2E is younger (less evolved) than Class 0 protostars.

Furthermore, we compare L1448 IRS2E to another source in the Perseus molecular cloud: SVS 13B (see Chen et al. 2009, and references therein). Like L1448 IRS2E, SVS 13B has no point-like infrared emission at wavelengths from 3.6 to 70 $\mu$m in the Spitzer images (also c2d data). However, it must be noted that SVS 13B is located $\sim 15''$ to the south of the bright Class I object SVS 13A, and thus the detection limits in the Spitzer images around SVS 13B are about 3 times worse than those in the L1448 images (because the imaging backgrounds around SVS 13B were raised by the bright source SVS 13A). Interestingly, SVS 13B is also driving a collimated outflow seen in the high angular resolution SiO and CO images (Bachiller et al. 1998, 2000). In contrast to L1448 IRS2E, SVS 13B has much stronger dust continuum emission at submillimeter and millimeter wavelengths and correspondingly has much higher gas mass ($>1 M_\odot$) and bolometric luminosity ($>1 L_\odot$). In addition, the kinematic properties of SVS 13B, e.g., fast rotation and subsonic turbulence (see Chen et al. 2009), are similar to those of Class 0 protostars (e.g., Chen et al. 2007). Therefore, SVS 13B is very likely more evolved than L1448 IRS2E and has already formed an extremely young Class 0 protostar.

Comparison to Known VeLLOs. The extremely low luminosity of L1448 IRS2E is similar to what is seen in the so-called very low luminosity objects (VeLLOs), an interesting subset of embedded, low-luminosity protostars (see Dunham et al. 2008, and references therein). However, non-detection at both 24 and 70 $\mu$m bands distinguishes L1448 IRS2E from all VeLLOs revealed thus far (Dunham et al. 2008). Direct observations, together with radiative transfer modeling, have shown that young (sub-) stellar objects have already formed in these VeLLOs. In contrast, there is yet no clear evidence for the presence of a protostar in L1448 IRS2E, even though the sensitivities of the Spitzer images of L1448 IRS2E are comparable to those used to detect the known VeLLOs (see Dunham et al. 2008, and references therein).

The evolutionary status and eventual final state of VeLLOs are still unclear. Some of them, e.g., IRAM 04191+1522 (see Dunham et al. 2006), represent typical Class 0 low-mass protostars, while others, e.g. L1014-IRS (see Bourke et al. 2005), could represent precursors of sub-stellar objects (i.e., proto-brown dwarfs). In the case of L1448 IRS2E, it is more likely that we are catching the very first moments of low-mass star formation because L1448 IRS2E already has about 0.04 $M_\odot$ of gas estimated from the SMA dust continuum observations, and more gas in the outer envelope/core can continue accreting onto it. If we assume a steady accretion rate and a core-to-star efficiency of 15%–30% (Evans et al. 2009), then it is very probable that a low-mass star ($\geq 0.1 M_\odot$) will eventually form in the L1448 IRS2E core.

4.3. A Candidate First Hydrostatic Core

The observational detection of the first hydrostatic core is of prime importance for understanding the early evolution of star-forming dense cores and the origin of outflows. Encouraged by these facts, searches for the first core have been undertaken over the past decade. Based on the HCO$^+$/H$^13$CO$^+$ observations, Onishi et al. (1999) suggested that L1521F could be a first core candidate, but Spitzer observations soon found that L1521F harbors a low-luminosity protostar (Bourke et al. 2006). More recent studies suggest that the evolutionary stage of L1521F
is similar to or younger than the Class 0 phase and may be consistent with the early second collapse phase (Shinnaga et al. 2009; Terebey et al. 2009). Another promising object was Cha-MMS1, suggested by Belloche et al. (2006) from the measurement of the deuterium fractionation. However, a mid-infrared source was detected by Spitzer MIPS observations, indicating a compact hydrostatic object had already formed in Cha-MMS (see Belloche et al. 2006 for more details).

Based on the SMA and Spitzer observations, we find that source L1448 IRS2E has the following characteristics: (1) it is not visible in the sensitive Spitzer infrared images (from 3.6 to 70 μm); (2) it has very weak (sub-) millimeter dust continuum emission and consequently has an extremely low bolometric luminosity (∼0.1 L⊙); and (3) it appears to drive a molecular outflow. Comparisons with prestellar cores and Class 0 protostars suggest that L1448 IRS2E is more evolved than prestellar cores but less evolved than Class 0 protostars, i.e., at a stage intermediate between prestellar cores and Class 0 protostars. These results are consistent with the theoretical predictions in the RHD/MHD models for the first hydrostatic core (see Section 1), making L1448 IRS2E the most promising first hydrostatic core candidate thus far.

However, it must be noted that the nature of source L1448 IRS2E is not definitive. More observations are needed to constrain its SED and to refine its outflow maps. Detections of other objects like L1448 IRS2E will be important for understanding the process of dynamical collapse and the origin of outflows. Sensitive surveys at wavelengths from far-infrared (e.g., Herschel) to (sub-) millimeter continuum (e.g., SCUBA) are needed to search for more first core candidates in nearby clouds. We also speculate that some of the objects in the current sample of prestellar cores may already harbor first cores, which drive molecular outflows hidden within the extended cloud emission and are therefore not revealed in low resolution single-dish observations. A systematic high-resolution interferometric CO survey toward these cores is needed to search for potential outflow activity.

5. SUMMARY

We present SMA and Spitzer observations of the low-mass, embedded dense core L1448 IRS2E. This core has no point-like infrared emission in the Spitzer images and shows weak emission in the SMA 1.3 mm dust continuum map (∼6 mJy). Consequently, it has an extremely low bolometric luminosity (less than 0.1 L⊙). Interestingly, the SMA CO (2–1) images suggest that L1448 IRS2E is driving a collimated CO outflow (up to ∼25 km s⁻¹), which is further supported by the Spitzer IRAC images with regards to the morphology of the outflow. L1448 IRS2E represents so far the lowest luminosity source with a detectable molecular outflow. A comparison with prestellar cores and Class 0 protostars suggests that L1448 IRS2E is in an evolutionary stage between that of a prestellar core and a Class 0 protostar. Our results are consistent with the predictions of the theoretical models for the first hydrostatic core, making L1448 IRS2E thus far the most promising first hydrostatic core candidate. Further observations, such as Herschel Space Observatory imaging at 75–300 μm and short-spacing CO observations, are needed to study its properties and to address more precisely its evolutionary status. If the properties of L1448 IRS2E are validated by further observations, this would be the first confirmed detection of the first core stage of star formation.

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