IRAS 16253–2429: THE FIRST PROTO-BROWN DWARF BINARY CANDIDATE IDENTIFIED THROUGH THE DYNAMICS OF JETS

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ABSTRACT

The formation mechanism of brown dwarfs (BDs) is one of the long-standing problems in star formation because the typical Jeans mass in molecular clouds is too large to form these substellar objects. To answer this question, it is crucial to study a BD in the embedded phase. IRAS 16253–2429 is classified as a very low-luminosity object (VeLLO) with an internal luminosity of \(<0.1 \, L_\odot\). VeLLOs are believed to be very low-mass protostars or even proto-BDs. We observed the jet/outflow driven by IRAS 16253–2429 in CO (2–1), (6–5), and (7–6) using the IRAM 30 m and Atacama Pathfinder Experiment telescopes and the Submillimeter Array (SMA) in order to study its dynamical features and physical properties. Our SMA map reveals two protostellar jets, indicating the existence of a proto-binary system as implied by the precessing jet detected in H$_2$ emission. We detect a wiggling pattern in the position–velocity diagrams along the jet axes, which is likely due to the binary orbital motion. Based on this information, we derive the current mass of the binary as \(\sim 0.032 \, M_\odot\). Given the low envelope mass, IRAS 16253–2429 will form a binary that probably consist of one or two BDs. Furthermore, we found that the outflow force as well as the mass accretion rate are very low based on the multi-transition CO observations, which suggests that the final masses of the binary components are at the stellar/substellar boundary. Since IRAS 16253 is located in an isolated environment, we suggest that BDs can form through fragmentation and collapse, similar to low-mass stars.

Key words: brown dwarfs – ISM: jets and outflows – ISM: molecules – stars: formation – stars: protostars

1. INTRODUCTION

The formation mechanism of brown dwarfs (BDs, mass \(<0.075 \, M_\odot\)) is a highly debated unsolved problem because the typical Jeans mass in molecular clouds is too large to form these substellar mass objects (Padoan & Nordlund 2004). Three formation mechanisms have been proposed. (1) In a molecular cloud, a fraction of the cores with BD mass may be compressed by the turbulent flow to reach sufficiently high densities for gravitational collapse to proceed (Padoan & Nordlund 2004). Oph-B11 was identified by André et al. (2012) as a pre-brown dwarf, namely, a starless core that will likely form a BD in the future, suggesting that this mechanism is a possible way to form a BD. This scenario is also supported by other works with identifications of BD candidates at early evolutionary stages (Barrado et al. 2009; Palau et al. 2014; Morata et al. 2015). (2) BDs are also considered to form in massive disks or multiple systems and can be ejected later (Reipurth & Clarke 2001; Bate et al. 2002; Rice et al. 2003; Stamatellos & Whitworth 2009; Basu & Vorobyov 2012). (3) The third mechanism suggests that BDs form near massive stars which drive strong winds to disrupt the envelopes of BDs before they can accrete sufficient material to form stars (Whitworth & Zinnecker 2004). Identifying the formation mechanism(s) requires that we study the early stage when a BD is still deeply embedded in its parental core, i.e., at the “proto-brown dwarf” stage (Barrado et al. 2009).

Discovered by the Spitzer Space Telescope, very low-luminosity objects (VeLLOs) are the faintest embedded protostars with internal luminosities of \(L_{\text{int}} < 0.1 \, L_\odot\) (Di Francesco et al. 2007). Through comparisons with the evolutionary tracks from models, the low internal luminosity implies that VeLLOs remain substellar (Young et al. 2004; Bourke et al. 2006; Huard et al. 2006) and are likely to form very low-mass stars or BDs in the future depending on their future accretion. Several VeLLOs have been considered to be proto-BD candidates in previous studies. Barrado et al. (2009) identified a proto-BD, J041757, in the Taurus molecular cloud based on the low luminosity and mass derived from its spectral energy distribution (SED). The low mass accretion rate of L328-IRS calculated from its outflows suggests that L328-IRS would attain at most a mass of \(0.05 \, M_\odot\) (Lee et al. 2013). Kaufmann et al. (2011) derived an unusually low density toward the natal core of L1148-IRS, implying that it could be a good BD candidate. Palau et al. (2014) found that IC 348-SMM2E will most likely remain substellar based on its low outflow force and low bolometric luminosity. As a result, VeLLOs could be some of the best targets for studying BDs in the embedded phase.

IRAS 16253–2429 (hereafter IRAS 16253) was first discovered as a Class 0 source by Kanzadiyan et al. (2004) in the \(\rho\) Oph star-forming region (\(d = 125\) pc; Evans et al. 2009). Later, Dunham et al. (2008) classified it as a VeLLO with an internal luminosity of \(\sim 0.08–0.09 \, L_\odot\). IRAS 16253 is located in a relatively isolated and quiescent portion in the east of the L1688 protocluster in the Ophiuchus molecular cloud complex. Thus, it can be used to test whether or not a BD can form in the same manner as a hydrogen-burning star. Tobin et al. (2012a) suggested that the central mass of IRAS 16253 is less than \(0.1 \, M_\odot\) by studying the kinematic structure of the parent core through \(N_2H^+\) observations with the Combined Array for Research in Millimeterwave Astronomy (CARMA). Yen et al. (2015) also estimated the mass of the central star to be \(0.02–0.04 \, M_\odot\) using a kinematic model for relatively small-scale C$^{18}$O emission using the Submillimeter Array (SMA).
addition, IRAS 16253 is believed to host a binary system based on the precessing H$_2$ jet detected by Khanzadyan et al. (2004; see Section 4.1.2). This suggests that the mass of each component in the binary system is even lower. To determine whether or not IRAS 16253 is a proto-BD binary system, we need to measure the masses of the protostellar objects accurately and derive the mass accretion from the parent core.

It is difficult to determine the mass of the central star of a young stellar object (YSO), especially in the embedded phase. One can fit the SED to obtain the photospheric luminosity and the effective temperature of the protostar and estimate the mass by comparing the value to evolutionary tracks (Huard et al. 2006). However, one SED may be reproduced by several sets of parameters (Robitaille et al. 2006, 2007) and the resulting mass is model dependent. Recently, the central masses of YSOs have been obtained with high angular resolution interferometric observations from kinematic models by assuming Keplerian rotation in the disk or envelope (Tobin et al. 2012a, 2012b; Murillo & Lai 2013; Yen et al. 2015). However, Keplerian rotation is difficult to detect in very low-mass objects such as proto-BDs; for example, neither Tobin et al. (2012a) nor Yen et al. (2015) found significant velocity gradients in IRAS 16253. The most reliable mass estimate is from resolving the binary rotation motion, which is mostly performed in pre-main-sequence stars as binary rotation is difficult to probe during the embedded phase. In this study, we trace binary orbital motion through the protostellar jets/outflows driven by IRAS 16253 and derive the mass of the central stars in order to identify IRAS 16253 as a proto-BD binary system.

The wiggling patterns of jets/outflows are used to probe the dynamics of binary systems. This method has been applied for several protostars (IRAS 20126+4104, Shepherd et al. 2000; L1551, Wu et al. 2009; HH211, Lee et al. 2010; L1448C, Hirano et al. 2010; L1157, Kwon et al. 2015). Wiggling patterns are believed to originate from (1) the orbital motion of the driving source or (2) the precession of the accretion disk caused by tidal interactions in a binary system. Both interpretations require the existence of a binary system, and the two origins can be distinguished by the mirror-symmetric (orbital) or point-symmetric (precession) locus in both position–velocity (PV) diagrams and images (Raga et al. 2009). The jet wiggling pattern caused by the orbital motion enables us to derive the orbital period, velocity, and binary separation, which allows us to determine the masses of the central stars.

In IRAS 16253, an S-shaped (point-symmetric) H$_2$ jet was detected at 2.12 μm by Khanzadyan et al. (2004) and in the mid-infrared by Barsony et al. (2010), but the spectral resolution was too low to probe the dynamics of the central stars. Stanke et al. (2006) used the James Clerk Maxwell Telescope (JCMT) to map the large-scale CO (3–2) emission from the outflows. However, the low-J CO emission is offset from the collimated H$_2$ jet, suggesting that they trace different gas. In addition, the low-J transitions suffer from optical depth effects, resulting in an underestimate of the outflow mass as well as the outflow force (Dunham et al. 2014; Yildiz et al. 2015). Gomez-Ruiz et al. (2013) further found that the molecular cloud and/or core emission could hide the outflows in low-velocity regions, which makes the estimation more uncertain.

In this paper, we analyze multi-transition CO observations obtained with single-dish telescopes (CO 2–1 with the IRAM 30m telescope, CO 6–5/7–6 with the Atacama Pathfinder Experiment, hereafter APEX) and an interferometer (CO 2–1 with the SMA). We use the high spectral and spatial resolution data to study the dynamical structure of IRAS 16253. Mid-J CO ($J = 6–5$ and $7–6$) emission traces the warm gas in protostellar outflows (Leurini et al. 2009; van Dishoeck et al. 2009; van Kempen et al. 2009a, 2009b, 2009c; Yildiz et al. 2012, 2015; Gomez-Ruiz et al. 2013) and is less affected by the issues noted above (Yildiz et al. 2015), which allows us to extract the outflow in low-velocity regions and to accurately determine the outflow mass and force.

2. OBSERVATIONS

2.1. SMA Observations

We observed IRAS 16253 using the SMA in its compact configuration in 2013 April. These observations targeted the 1.3 mm dust continuum emission and three molecular lines: CO (2–1) at 230.538 GHz, $^{13}$CO (2–1) at 219.560 GHz, and N$_2$D$^+$ (3–2) at 231.321 GHz. The primary beam is about 53″ and the synthesized beam is 25″×47″ for CO (2–1). It is only slightly different for the other lines. High spectral resolution windows were used for the C$^{18}$O (2–1) and N$_2$D$^+$ (3–2) lines with 512 channels over 104 MHz, and for CO (2–1) with 256 channels over 104 MHz. The resulting spectral resolutions are $\sim$0.28 km s$^{-1}$ for C$^{18}$O (2–1), $\sim$0.26 km s$^{-1}$ for N$_2$D$^+$ (3–2), and $\sim$0.53 km s$^{-1}$ for CO (2–1). We used 3C279 as a bandpass calibrator, J1626-298 as a gain calibrator, and Neptune as a flux calibrator ($\sim$10.5 Jy$^{-1}$) for all of our observations. The raw data were calibrated using the MIR package (Qi 2005) and the calibrated data were further imaged using MIRIAD (Sault et al. 1995).

The observations included (1) deep observations centered on the position of the infrared source ($\alpha = 16^h28^m21^s.6$, $\delta = -24^\circ 36′23″.4$, J2000) in order to detect the dust continuum emission and weak molecular lines, and (2) a mosaic for mapping the large-scale CO outflows toward three pointings: one at the northeast of the central field and the other two at the southwest of the central field. The three pointing positions, combined with the central pointing position (four positions in total), are distributed along the outflow axis with an interval of $\sim$20″. The deep observations contained one track using five antennas and one track using seven antennas. The on-source integration time was $\sim$5 hr for each track and the sky opacity at 225 GHz was about 0.1. These two data sets were later combined to increase the sensitivity. For the mosaic mapping, one track was also taken with $\sim$5 hr of total on-source integration time for three positions using seven antennas. The sky opacity at 225 GHz was about 0.08 during the observations.

2.2. Jansky Very Large Array (JVLA) Observations

The JVLA observations were carried out in 2013 June toward the source center in the C configuration at 43 GHz. The total observing time was about 3 hr. The gain, bandpass, and flux calibrators were J1625-2527, J1256-0547, and J1331+3030, respectively. We used the Two 1 GHz mode with a total of 16 subbands. The bandwidth of each subband was 128 MHz. All but one of the subbands have a channel width of 1 MHz. Only one

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8 http://sma1.sma.hawaii.edu
subband was set to a higher spectral resolution of 31.3 kHz for observing SiO (1–0) at 43.424 GHz. The synthesized beam size is 1″ × 0.5″. We used the calibrated visibilities processed through the VLA CASA (Common Astronomy Software Application) calibration pipeline. The image in this paper was produced with CASA.

2.3. IRAM 30 m CO (2–1) Observations

The CO (2–1) observations were carried out in 2014 June using the 30 m telescope of the Institute for Radio Astronomy in the Millimeter range (IRAM). The total observing time was about 9.5 hr and the sky opacity during the observations was 0.16–0.31. The pointing and focus were checked every one to two hours and the pointing corrections were between 2″ and 7″. We used the E230 receiver and the FTS backend with a channel width of 50 kHz (∼0.06 km s⁻¹). The data were later resampled to a channel width of 0.1 km s⁻¹. We used the on-the-fly mode to map a region of 84″ × 228″ with a position angle of 21° (east from north) and an angular resolution of ∼11″/230 GHz. The data were scaled from T_{MB} to T_{RMS} using a main beam efficiency of 0.58 and a forward efficiency of 0.92 taken from the IRAM 30 m website.²

2.4. APEX CO (6–5)/(7–6) Observations

We used the Carbon Heterodyne Array of the MPIfR (CHAMP³) at APEX (Kasemann et al. 2006; Güsten et al. 2008) to simultaneously observe CO (6–5) and (7–6) in 2014 May. The total observing time was about 12.5 hr with a precipitable water vapor (PWV) in the range ∼0.4–0.7 mm. The pointing and focus were checked every ∼1.5 hr and the pointing accuracy was found to be better than 1″. The AFFTS backend was used with two overlapping 1.5 GHz units per pixel, resulting in a 2.8 GHz bandwidth and a spectral resolution of 212 kHz (∼0.09 km s⁻¹) for 6–5 and 0.08 km s⁻¹ for 7–6. The data were later resampled to a channel width of 0.1 km s⁻¹. The on-the-fly mode was used to map an area with a size of 80″ × 300″ with a position angle of 21° centered on the infrared source. The beam sizes are about 9″ for CO (6–5) and 8″ for CO (7–6) with sampling every 3″. The data were smoothed to a resolution of 11″/2 for comparison with the IRAM data. The main beam efficiencies were set to 0.41 for CO (6–5) at 691.5 GHz and 0.34 for CO (7–6) at 806.7 GHz, and the forward efficiency was set to 0.95 at both frequencies.⁶

3. RESULTS

3.1. Central Source—SMA and JVLA Images

Figure 1 (left panel) shows the continuum emission at 43 GHz from JVLA and 224 GHz from SMA. They peak at the position of the infrared source, although the resolutions of the two data sets are very different. The dust emission at 224 GHz has a peak intensity of 16.7 mJy beam⁻¹. The source size is found to be 5″ × 4″/6 in FWHM by fitting a two-dimensional Gaussian and the deconvolved source size is 3″/4 × 2″/3. The expected binary system, if it exists (see Section 4.1.2), is not resolved by SMA observations with a synthesized beam size of 4″/0 × 2″/8 at a position angle of 3°6. A point source was detected by JVLA at the position of the infrared source with a peak intensity of ∼0.12 mJy beam⁻¹. The binary system was also not resolved by the JVLA observations, with an angular resolution of 1″1 × 0″5, implying that the separation is extremely small. However, another possibility is that the companion is too faint to detect at 43 GHz since the signal-to-noise ratio (S/N) of the detected point source is only ∼5.9.

Figure 1 (right panel) shows our C18O (2–1) and N2D⁺ (3–2) integrated intensity maps. The C18O emission has a FWHM of 5″/7 × 4″/7 and a deconvolved size of 4″/2 × 2″/8. The emission peaks at the position of the infrared source, similar to the 224 GHz continuum emission, whereas the N2D⁺ (3–2) emission is point-like and peaks to the north of the infrared source at a distance of about 2″/6 (325 au in projection). The true distance could be larger than the projected distance if the C18O and N2D⁺ emission comes from a flattened structure perpendicular to the outflow axis, which is expected to lie close to the plane of the sky due to the collimated extended emission. The systemic velocities are found to be 4.01 ± 0.04 km s⁻¹ for the C18O emission and 3.85 ± 0.05 km s⁻¹ for the N2D⁺ emission from hyperfine structure fitting, although the fitting result for C18O may be affected by its slightly asymmetric line profile which skews toward the blue.

3.2. Jets/outflows from SMA Observations

The SMA CO (2–1) integrated intensity map reveals two collimated components (Figure 2). Both components contain blueshifted emission and redshifted emission which are likely bipolar jets/outflows from the central submillimeter source. One component lies along the northeast–southwest direction (hereafter NE–SW), and the other is approximately along the north–south direction (hereafter N–S) in the plane of the sky. Each of them could trace either an outflow cavity wall or a jet. Via scattered light, the outflow cavity is clearly seen in the IRAC 1 image (Figures 1 and 2) and exhibits a bipolar, symmetric, hourglass shape (Barsony et al. 2010). The N2H⁺ (1–0) emission likely highlights the dense region carved by the bipolar outflows. This emission is not seen toward the outflow cavity, especially on the side of the blueshifted lobe. For the redshifted lobe, the N2H⁺ emission partially overlaps with the cavity, which may be explained by projection effects; some N2H⁺ might be distributed in front of the outflow cavity. The NE–SW CO (2–1) component is well separated from the edges of the outflow cavity traced by the near-infrared scattered light at 3.6 μm (Figure 2(a)). In addition, the NE–SW component matches well the H₂ emission (Figure 2(b), the H₂ image is obtained from the CFHT observations by T. Hsieh et al. 2016 in preparation) which exhibits a distinct S-shaped pattern and clearly does not follow the cavity edge (Barsony et al. 2010); the CO emission continuously extends from the central source to the H₂ emission, whereas the H₂ emission is detected in three isolated patches. The southernmost H₂ patch in Figure 3 does not have associated SMA CO emission because it is outside the field of view of our SMA observations. As a result, the NE–SW CO (2–1) component is most likely associated with the H₂ jet rather than with the wall of the outflow cavity. The N–S CO (2–1) component is detected toward IRAS 16253 for the first time. Similar to the NE–SW component, the N–S component is not distributed along the edge of the outflow.

² http://casa.nrao.edu
³ http://www.iram.es/IRAMES/mainWiki/Iram30mEfficiencies
⁴ http://www3.mpifr-bonn.mpg.de/div/submmtech/heterodyne/champplus/champ_efficiencies.16-09-14.html
seen in the IRAC 1 image. This suggests that the N–S component traces another jet, even if there is no H2 emission associated with it. The loci of both the NE–SW and N–S components are curved and likely have a point symmetry at the source center. Hereafter, we call these two components the NE–SW jet and N–S jet.
3.3. Jets/outflows from IRAM 30 m and APEX Observations

The CO (2–1), (6–5), and (7–6) integrated intensity maps are shown in Figure 14. For better comparison, the CO (6–5) and (7–6) maps were smoothed to the angular resolution of the CO (2–1) map (11′′/2), and all of the maps were constructed in the same grid with a pixel size of 5″. Because the CO emission traces both the outflows and the large-scale structures of the molecular cloud, we applied a multiresolution analysis (Belloche et al. 2011) to the channel maps in order to remove the cloud emission (see Section 4.1.1). Figures 3 and 14–20 show the integrated intensity and channel maps after filtering the large-scale emission produced by the molecular cloud.

The molecular outflows detected in CO (2–1) and (6–5) are extended up to ∼2′−3′ (15,000−23,000 au) from the source center. For both CO (2–1) and (6–5), the blueshifted outflows are much weaker than the redshifted outflows. However, the spatial and velocity distributions are very different between CO (2–1) and (6–5), as shown in the integrated intensity maps (Figure 3) and channel maps (Figures 15 and 17). The CO (6–5) emission tends to be stronger than that of CO (2–1) at low velocity; CO (6–5) is much brighter in the velocity ranges of ∼2.3−3.5 km s⁻¹ (blueshifted) and ∼4.4−6.4 km s⁻¹ (redshifted), while CO (2–1) is brighter in the velocity ranges of ∼0.9−2.6 km s⁻¹ (blueshifted) and ∼4.7−7.1 km s⁻¹ (redshifted). In addition, in the low-velocity range of ∼4.7−5.0 km s⁻¹, CO (2–1) is undetected in the inner region where the CO (6–5) emission is bright. For the blueshifted outflow lobe, the CO (6–5) emission is distributed from the driving source to its northeast at a distance of ∼100″, and CO (2–1) is only seen at a distance of ≥40″ (Figure 3). The CO (2–1) blueshifted outflow is likely extended over a larger region than our IRAM 30 m map, which was designed to cover only the jet region detected in H₂.

CO (7–6) is detected in an even lower velocity range than CO (2–1) and (6–5) (Figures 3 and 19). Spatially, CO (7–6) is mostly detected in the inner 1″ region but the S/N is low. The CO (7–6) emission can be separated into two components. A compact component toward the center is seen in the velocity range ∼3.3−4.1 km s⁻¹ for which there is no detection in CO (2–1) and (6–5). An elongated component is detected in the velocity ranges of ∼2.3−2.9 km s⁻¹ (blueshifted) and ∼4.3−5.4 km s⁻¹ (redshifted) which are associated with the collimated H₂ jet.

A particularly intriguing result is found when comparing the CO data with the shock tracer H₂ (Figure 3). We find that the CO (7–6) and (6–5) integrated intensities match well the locus of the H₂ jet, which has an “S-shaped” point symmetry around the driving source. In contrast, the CO (2–1) integrated intensity is shifted to the east of the H₂ jets. It likely probes the outflow entrained gas and cavity wall detected in scattered light with IRAC 1.

Figure 4 shows a comparison of the SMA CO (2–1) integrated intensity map with the single-dish CO integrated intensity maps. The redshifted component of the N–S jet from the SMA map is also detected with the IRAM 30 m telescope. However, the SMA NE–SW jet associated with the H₂ jet is likely hidden by the large-scale outflow emission and/or cloud emission in the IRAM CO (2–1) map. Nevertheless, the warm
gas tracers CO (6–5)/(7–6) do trace the NE–SW jet very well (Figures 4(b) and (c)).

Blueshifted emission is detected in the southern part of the CO (2–1) integrated intensity map (Figure 3(a)) and channel map (Figure 15). This emission can also be seen in the IRAM and SMA CO (2–1) PV diagrams (see Sections 4.1.2 and 4.1.3). The component extends outside the outflow cavity (Figure 3) and its systemic velocity of ~0.7–1.6 km s\(^{-1}\) (Figure 15) is relatively lower than the blueshifted outflow in all of the single-dish and SMA maps. Thus, this component is most likely not associated with the outflows. Because its systemic velocity is also different from that of IRAS 16253 as well as the Ophiuchus molecular cloud, we speculate that this blueshifted emission originates from some background sources.

4. ANALYSIS

4.1. Dynamical Features of the Molecular Jets/Outflows

4.1.1. Filtering of the Large-scale Emission

Our single-dish CO (2–1)/(6–5)/(7–6) maps are severely contaminated by large-scale cloud emission, especially for the CO (2–1) transition. To remove this extended emission, we applied a multiresolution analysis to the channel maps. This method (see Appendix C in Belloche et al. 2011 for details) is based on a median filter which extracts the structures at different scales of \(< 2^\circ + 1\) pixels, where \(i = 1, 2, 3, 4, 5,\) and 6 with a pixel size of 5″. The multiresolution analysis decomposes the initial map into maps containing small-scale structures (summation maps) and corresponding maps containing large-scale structures (smooth maps). For example, in step 3 \((i = 3)\), the summation map includes structures at scales \(< 9\) pixels and the smooth map contains structures at scale \(> 9\) pixels; the sum of these two maps is strictly equal to the input (observed) map. We checked the outcome of this decomposition at each step in order to select the step at which the outflow emission and cloud emission are best separated. As a result, we adopted step 4 for CO (2–1), step 5 for CO (6–5), and step 4 for CO (7–6). We plot the integrated intensity summation maps, smooth maps, and input maps in Figure 14. The channel summation maps and channel smooth maps are shown in Figure 5.
Figures 15–20. In the following, we use the summation maps at the specific steps to derive the outflow properties. The removal of large-scale emission appears to be crucial to derive the outflow properties, especially for CO (2–1) for which the contribution of the cloud could even be a few times stronger than the contribution of the outflows.

The multiresolution analysis is also used to extract the jet (knot) from the outflow cavity. After the removal of cloud emission, we used the step 3 summation maps to separate the collimated NE–SW jet and the extended outflow cavity in CO (6–5) (Figure 5). We applied the multiresolution analysis to the step 5 summation map of CO (6–5) such that the sum of the two contour maps in Figure 5 is equal to that in Figure 3(b).

The integrated intensity summation map matches the H$_2$ jets well, while the peak of its corresponding smooth map is shifted to the east as in the CO (2–1) map; the smooth map here includes only the extended structures in the outflows while the large-scale cloud emission has already been removed. This result suggests that the small-scale emission may trace the collimated jet and/or the jet knots. In contrast, the large-scale structures are sensitive to the entrained gas and/or the outflow cavity wall.

### 4.1.2. Precessing Jets

The S-shaped jet driven by IRAS 16253 was first detected by Khanzadyan et al. (2004) through H$_2$ emission at 2.12 μm (NE–SW). S-shaped jets are believed to originate from precessing disks (Masciadri & Raga 2002; Raga et al. 2009; Lee et al. 2010).

undergoing tidal interactions with a close companion; in other words, IRAS 16253 is likely a proto-binary system. The SMA CO (2–1) and APEX CO (6–5) observations reveal the NE–SW jet locus and further connect the H$_2$ patches. Although the N–S “jet” is not associated with H$_2$ emission, it matches the component seen in the IRAM CO (2–1) map in the relatively high-velocity range of 7.85–9.05 km s$^{-1}$ (Figure 6(b)). In addition, it does not coincide with the edge of the cavity seen in scattered light (Figure 2). Therefore, we suggest that the N–S component is a newly discovered jet driven by a binary component. Furthermore, the IRAM CO (2–1) map covers a larger region than the SMA map and reveals a further extension and probably the head of the N–S jet (Figure 6(b)). Given the absence of H$_2$ emission and absence/weakness of CO (6–5) emission in the N–S jet, the NE–SW and N–S jets must have very different physical conditions, despite their similar environmental conditions in a common envelope.

We modeled the jet locus of both the NE–SW and N–S jets by considering bipolar jets originating from precessing disks. An edge-on precessing jet can be described by a sinusoidal pattern with an amplitude increasing with distance from the driving source (Eislöffel et al. 1996). Taking the outflow inclination into account, Wu et al. (2009) revised the formula from Eislöffel et al. (1996) to analyze the precessing outflow driven by L1551 IRS5 as

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos \psi - \sin \psi \\ \sin \psi \cos \psi \end{bmatrix} \left[ \frac{a l \sin(2\pi l/\lambda_{pre} + \phi_{0,pre})}{l \cos(\theta_{inc})} \right].$$ (1)
Notes. Column (1): Jet component. Column (2): Position angle of the jet. Column (3) Precession amplitude; Column (4): Spatial period of the jet precession. Column (5): Initial phase of precessing jet. Column (6): Inclination angle of the jet. Column (7): Half-opening angle of the precession cone. Column (8) Jet velocity.

\( a \) The inclination is adopted based on the morphology.

\( b \) \( \alpha' \) represents the angle between the precessing jet and its symmetry (precession) axis, which is obtained by \( \alpha' = \arctan(\alpha) \).

\( c \) Jet velocity estimated based on the PV diagram of the APEX data.

where \( x \) and \( y \) are the Cartesian coordinates, \( \alpha \) is the precession amplitude, \( \lambda_{\text{pre}} \) is the precession spatial period, \( l \) is the distance from the source, \( \phi_{0,\text{pre}} \) is the initial phase at the source position, \( \psi \) is the position angle of the jet symmetry (precession) axis in the plane of the sky, and \( \theta_{\text{inc}} \) is the inclination angle (\( \theta = 0 \) for edge-on). The distance \( l \) in Equation (1) is a true distance (as well as \( \alpha \) and \( \lambda_{\text{pre}} \)) rather than a projected distance due to \( \cos(\theta_{\text{inc}}) \). However, \( \lambda_{\text{pre}} \), \( l \), and \( \theta_{\text{inc}} \) are degenerate (only two free parameters), which prevents us from deriving the inclination angle. Note that although the inclination angle is included, Equation (1) is only suitable for cases with small inclination angles; the sinusoidal pattern with increasing amplitude is only an approximation of a helical pattern in side view.

Based on the outflow morphology, we choose a nominal inclination angle of 20° (with respect to the plane of the sky), which is close to the 15° estimated by Yen et al. (2015), in order to derive \( \alpha \), \( \lambda_{\text{pre}} \), \( \phi_{0,\text{pre}} \), and \( \psi \). The fact that the outflow is spatially extended and collimated implies that the jet/outflow most likely lies close to the plane of the sky. However, there is almost no overlap between the blueshifted emission and the redshifted emission, which excludes an edge-on configuration (Cabrit & Bertout 1990).

Our assumption of 20° is therefore a reasonable value. The physical parameters affected by the choice of the inclination angle are discussed in Sections 4.1.3 and 4.2.2. The fitting process considers the H2 emission, the APEX CO (6–5) outflow map, and the SMA CO (2–1) map for the NE–SW jet (Figure 6(a)), and the IRAM 30 m high-velocity map and SMA CO (2–1) map for the N–S jet (Figure 6(b)). We choose several peak positions along the jet to fit with Equation (1). The best-fit loci of the NE–SW and N–S jets are shown in Figure 6 and the parameters of this best-fit model are listed in Table 1.

To trace the dynamics of the jets, we plot a special PV diagram with its PV cut along the jet locus from the precession models in Figure 6. Note that the position in our PV diagram is the projected distance to the source along the jet symmetry axis in the plane of the sky (i.e., P.A. in Table 1), not the distance along the (curved) jet locus. This enables us to convert the distance in the PV diagram into a dynamical age for the jet, which makes our following analysis easier, especially for modeling the orbital motion of a binary system (Section 4.1.3).

Figure 7 shows the PV diagram for the IRAM CO (2–1) and APEX CO (6–5) in the NE–SW jet. The precessing jet in the PV diagram can be described with an arc structure:

\[ D = l \cos(\theta_{\text{inc}}), \]  

where \( D \) is the projected distance to the source, \( V_{\text{LOS}} \) is the velocity along the line of sight, and \( \alpha' \) is the half-opening angle of the precession cone and can be obtained by \( \alpha' = \arctan(\alpha) \) (Wu et al. 2009). The positive and negative signs in Equation (2b) are used for the red and blueshifted lobes, respectively. We have derived these parameters by fitting the jet locus (Equation (1)), except for \( V_{\text{jet}} \) which is determined by the arc line position along the velocity axis in the PV diagram (Figure 7). We estimate a jet velocity from the CO (6–5) PV diagram since the APEX CO (6–5) map likely traces the NE–SW jet better than the IRAM CO (2–1) map. However, the CO (6–5) map also contains the emission from the outflow cavities, which suggests that the jet velocity of 6.0 km s\(^{-1}\) may be underestimated. Obtaining the jet velocity from the interferometer could be more reasonable because it is more sensitive at smaller scales (see Section 4.1.3). We note that the distance
in Equation (2a) is an approximation which does not take into account the contribution of the precession motion that produces the velocity

$$V_{\text{pre}} = V_{\text{jet}} \sin(\alpha') \cos(2\pi t / \lambda_{\text{pre}} + \phi_{0,\text{pre}})$$

(3)

in Equation (2b). However, the approximation is reasonable for the small inclination angle $\theta_{\text{inc}}$ and half-opening angle of the precession cone $\alpha'$.

4.1.3. Orbital Wiggling in the Outflows

In addition to precession caused by the tidal interaction between the noncoplanar disk and the close companion, the binary orbital motion can also affect the jet locus and produce a small-scale wiggling pattern in both the jet map and PV diagram (Raga et al. 2009; Wu et al. 2009; Hirano et al. 2010). Figure 8 shows the PV diagram of the SMA CO (2–1) data for both the NE–SW and N–S jets along the jet locus in the same way as we did for the single-dish data (Figure 7). The SMA data have a higher angular resolution, but a lower spectral resolution and a smaller field of view than the single-dish data.

In the SMA PV diagram, we see small condensations that seem to oscillate in the velocity direction. We propose that these oscillations are due to the binary orbital motion. Such oscillations are not seen in the PV diagrams of the single-dish data because the spatial resolution ($\sim 11''/2$) is insufficient to resolve the wiggling pattern with a spatial period of $\sim 40''$. In order to study the wiggles in the SMA PV diagrams, we add the effect of orbital motion

$$V_{\text{orb,rad}} = V_{\text{orb}} \cos \left( \frac{V_{\text{orb}} t + \phi_{0,\text{orb}}}{R} \right)$$

(4)

into Equation (2) (also see Equation (3)):

$$V_{\text{LOS}} = V_{\text{LSR}} \pm V_{\text{jet}} \cos(\alpha') \sin(\theta_{\text{inc}})$$

$$+ \left( V_{\text{pre}} + V_{\text{orb,rad}} \right) \cos(\theta_{\text{inc}})$$

(5)

where $V_{\text{orb}}$ is the orbital velocity, $V_{\text{orb,rad}}$ is the projection of the orbital velocity along the line of sight if the inclination angle is 0, $R$ is the orbital radius, $t$ is time, and $\phi_{0,\text{orb}}$ is the initial phase at the source position. To derive the orbital parameters, we fit the PV diagram with Equation (5). We select the peak velocity in each position as our data points in the PV diagram, for which we chose a threshold of $S/N > 5$. We set the weighting for each data point as an integer calculated from $w = (S/N)/5$. Finally, we artificially remove those points which are not associated with the jets. The best-fit model and the data points are shown in Figure 8 and its parameters are listed in Table 2. Since the wiggling structure can be better seen in the NE–SW jet than in the N–S jet, the fitting process is mainly based on the NE–SW jet. We first derive the jet velocity, orbital velocity, orbital radius, and initial phase of the NE–SW jet. Consequently, only two free parameters (jet velocity and orbital velocity) remain undetermined in the N–S jet, since the orbital velocity is proportional to the radius $\left( \frac{R}{V_{\text{orb},1}} = \frac{R_0}{V_{\text{orb},1}} \right)$ and the phases have a difference of $180^\circ$ in a binary system. Although the determinations of the data points is quite artificial in the fitting procedure, the significance of the orbital velocity

Table 2: Model Parameters of The Orbital Jets

| Jets      | $R$ (arcsec) | $\phi_{0,\text{orb}}$ (degree) | $V_{\text{jet}}$ (km s$^{-1}$) | $V_{\text{orb}}$ (km s$^{-1}$) | $V_{\text{LSR}}$ (km s$^{-1}$) |
|-----------|-------------|--------------------------------|-------------------------------|--------------------------------|--------------------------------|
| NE–SW     | 0.45        | 326 $\pm$ 4                    | 7.3 $\pm$ 0.05                | 0.52 $\pm$ 0.02                | 3.5 $\pm$ 0.01                 |
| N–S       | 0.10        | 146 $\pm$ 4                    | 4.2 $\pm$ 0.03                | 0.12 $\pm$ 0.04                | 3.5 $\pm$ 0.01                 |

Note. Column (1): Jet component. Column (2): Radius of the binary orbital motion. Column (3): Initial phase for orbital motion at the source. Column (4): Jet velocity. Column (6): Orbital Velocity of the corresponding driving source. Note that Columns (2) and (4) have a relation $\frac{R_{0,\text{orb}}}{V_{\text{orb},1}} = \frac{R_0}{V_{\text{orb},1}}$, where the subscripts 1 and 2 denote the two jets. The two jets have a phase difference of $180^\circ$ due to the orbital motion of the binary system.
(\(V_{\text{orb}} = 0.53 \pm 0.02 \text{ km s}^{-1}\), with more than 26\(\sigma\) confidence level) for the NE–SW jet suggests that the wiggles produced by \(V_{\text{orb}}\) in Equations (4) and (5) are trustworthy. For the N–S jet, the orbital velocity 0.1 ± 0.03 km s\(^{-1}\) with the confidence level of ∼3\(\sigma\) is insufficient to support the existence of oscillation. Nevertheless, the orbital velocity and radius (as well as period) of the NE–SW jet-driving source is independent of the result of the fit of the N–S jet and should be reliable. As a result, the best-fit model implies a very small binary separation of ∼0″55 which is consistent with the SMA and JVLA continuum observations (see Section 4.2.1).

Figure 8 also includes the best-fit model assuming a systemic velocity of 4 km s\(^{-1}\) based on the \(N_2H^+\) (1–0) observations toward the parent core (Tobin et al. 2012a; Hsieh et al. 2015). However, this model is not adopted since \(N_2H^+\) (1–0) does not necessarily trace the systemic velocity of the central objects. On the other hand, with the systemic velocity kept as a free parameter, the best-fit yields \(V_{\text{LSR}} \sim 3.5 \text{ km s}^{-1}\), which is close to the velocity of 3.4 km s\(^{-1}\) found by Stanke et al. (2006) on the basis of the CO (3–2) outflow observations.

### 4.1.4. Orbital Evolution and Mass Accretion Models

The early evolution of binary systems has been a long-standing problem and is still poorly understood. The evolution of the multiplicity frequency has recently been studied based on high-resolution interferometric surveys (Reipurth et al. 2014). Several studies have resolved a number of multiple systems at the Class 0/I stage (Looney et al. 2000; Chen et al. 2008, 2009; Maury et al. 2010; Enoch et al. 2011; Tobin et al. 2013). The most thorough survey was presented in Chen et al. (2013), and they found the multiplicity frequency of Class 0 protostars to be approximately twice as high as that of Class I sources and pre-main-sequence stars, which could be interpreted as binary evolution (migration) in the early stages (Zhao & Li 2013). Note that Chen et al.’s sample includes IRAS 16253, but they did not resolve the binary system.

Our best fit of the jet wiggling pattern in the PV diagram (Figure 8) leads to a problem: we do not see the wiggles due to the orbital motion in the jet in the spatial domain. Figure 9(a) shows the predicted spatial wiggling pattern corresponding to the best-fit model in the PV diagram in which the southernmost patch of \(H_2\) emission is not fit. We propose that a time-variable orbital motion could be the answer to this problem. Here, we provide several simple models to approach the problem considering migration and mass accretion.

We start from Kepler’s third law:

\[
P_{\text{orb}}^2 = \frac{4\pi^2a^3}{GM_{\text{tot}}},
\]

where \(P_{\text{orb}}\) is the orbital period, \(a\) is the binary separation, and \(M_{\text{tot}}\) is the total mass of the central objects. Thus, the orbital velocity and period have the following relations with \(M_{\text{tot}}\) and \(a\):

\[
V_{\text{orb}} \propto \left(\frac{M_{\text{tot}}}{a}\right)^{1/2}, \quad P_{\text{orb}} \propto \left(\frac{a^3}{M_{\text{tot}}}\right)^{1/2}
\]

Considering the binary separation \(a\) (i.e., \(R_1 + R_2\)) as a function of time \(a(t)\), we replace the orbital velocity and binary separation in Equation (5) by the time-dependent functions \(V_{\text{orb}}(t)\) and \(R(t)\) assuming a constant total mass \(M_{\text{tot}}\). Three models with time-dependent separation are shown in
Figure 10(a): one model with a constant orbital radius and two models with an orbital radius decreasing or increasing by 2% per 1000 years, respectively. To study the evolution, Figure 10 also shows the time axis on the right-hand side, which is obtained assuming a jet velocity of 7.3 km s\(^{-1}\) and an inclination angle of 20° (see Table 2). Compared to the model with constant separation (solid line in Figure 10(a)), the model with increasing separation clearly shows a growing period as the system evolves (in the direction toward the driving source position), whereas the model with decreasing separation displays the opposite behavior.

Because of the ongoing accretion process onto the central objects, we actually expect \( M_{\text{tot}} \) to increase with time. Therefore, we replace the constant mass \( M_{\text{tot}} \) in Equation (7) with a time-variable factor \( M_{\text{tot}}(t) \). We set the models with an initial mass of 10% of the current mass and a constant mass accretion rate over its dynamical time (1.3 × 10\(^4\) year). The results of these models are shown in blue in Figures 9(b) and 10(b) where a possible variation of the binary separation is also included (+2%, 0%, and −2% per 1000 years). Furthermore, in Figures 9(c) and 10 (c), we present another model to mimic an episodic accretion process with 90% mass accretion between −6000 and −5000 years (black lines). We find that both continuous and episodic accretion models have the jet loci go through the southernmost \( \text{H}_2 \) patch (Figures 9(b) and (c)). However, all of these modeled loci slightly deviate from the \( \text{H}_2 \) emission in the northern part of the NE–SW jet. We suggest that the models with mass increments are possible approaches to the problem of the absence of the wiggling pattern, but it may require more complicated models or simulations than our simple description. Furthermore, it is likely that the modeled loci in the PV diagram (Figure 10) would allow us to determine the mass accretion history if high angular and spectral resolution data covering the whole jet are presented. With such additional data, our models may provide an opportunity to study the mass accretion history and/or the orbital evolution (migration) in a binary system through the wiggling pattern of the molecular jets/outflows.

4.2. Physical Conditions

4.2.1. Central Object

The SMA continuum emission at 224 GHz toward the center is resolved with a deconvolved FWHM size of 3″4 × 2″3. The continuum flux of the central object at 224 GHz \( S_{1.3 \text{mm}} \) is 37.7 ± 0.15 mJy, which is about 10% less than the flux reported in
Table 3  
Outflow Parameters

| Velocity Range (km s\(^{-1}\)) | SMA CO (2–1) NE–SW\(^a\) | SMA CO (2–1) N–S\(^a\) | IRAM–APEX\(^b\) |
|---------------------------------|-----------------------------|-----------------------------|-----------------------------|
|                                 | Blue            | Red              | Total            | Blue            | Red              | Total            | Blue            | Red              | Total            |
|                                 | 0.3–3.0        | 4.6–9.8          | Total            | 0.7 to 3.0      | 4.6–10.9        | Total            | 0.55–2.75       | 4.45–7.35        | Total            |

\[ \theta_{\text{inc}} = 20^\circ \]

- **Mass**
  \[ \times 10^{-4} M_\odot \]
  - Blue: 0.80\(\pm\)0.31
  - Red: 2.95\(\pm\)1.96
  - Total: 3.75\(\pm\)4.99

- **Momentum**
  \[ \times 10^{-3} M_\odot \text{ km s}^{-1} \]
  - Blue: 0.43\(\pm\)0.06
  - Red: 1.96\(\pm\)2.61
  - Total: 2.39\(\pm\)3.18

- **Outflow forces (F\(_{\text{CO}}\))**
  \[ \times 10^{-7} M_\odot \text{ km s}^{-1} \text{ yr}^{-1} \]
  - Blue: 0.81\(\pm\)0.10
  - Red: 2.98\(\pm\)1.17
  - Total: 3.79\(\pm\)5.04

- **Kinetic luminosity (L\(_{\text{kin}}\))**
  \[ \times 10^{-4} L_\odot \]
  - Blue: 0.80\(\pm\)0.31
  - Red: 3.83\(\pm\)5.88
  - Total: 4.63\(\pm\)8.17

- **Mass-loss rate (M\(_{\text{loss}}\))**
  \[ \times 10^{-8} M_\odot \text{ yr}^{-1} \]
  - Blue: 1.49\(\pm\)0.58
  - Red: 4.50\(\pm\)1.77
  - Total: 5.98\(\pm\)2.35

\[ \theta_{\text{inc}} = 20^\circ \]

- **Mass**
  \[ \times 10^{-4} M_\odot \]
  - Blue: 0.80\(\pm\)0.31
  - Red: 2.95\(\pm\)1.96
  - Total: 3.75\(\pm\)4.99

- **Momentum**
  \[ \times 10^{-3} M_\odot \text{ km s}^{-1} \]
  - Blue: 0.15\(\pm\)0.06
  - Red: 0.67\(\pm\)0.89
  - Total: 0.82\(\pm\)1.09

- **Outflow forces (F\(_{\text{CO}}\))**
  \[ \times 10^{-7} M_\odot \text{ km s}^{-1} \text{ yr}^{-1} \]
  - Blue: 0.10\(\pm\)0.03
  - Red: 0.37\(\pm\)0.50
  - Total: 0.47\(\pm\)0.63

- **Kinetic luminosity (L\(_{\text{kin}}\))**
  \[ \times 10^{-4} L_\odot \]
  - Blue: 0.03\(\pm\)0.01
  - Red: 0.16\(\pm\)0.22
  - Total: 0.20\(\pm\)0.26

- **Mass-loss rate (M\(_{\text{loss}}\))**
  \[ \times 10^{-8} M_\odot \text{ yr}^{-1} \]
  - Blue: 0.54\(\pm\)0.71
  - Red: 1.64\(\pm\)2.19
  - Total: 2.18\(\pm\)2.89

**Notes.**
- The outflow parameters are derived by assuming an H\(_2\) density of 10\(^5\) cm\(^{-3}\) and a \(T_{\text{kin}}\) of 40 K. The upper and lower limits correspond to calculations assuming a lower \(T_{\text{kin}}\) of 30 K and a higher \(T_{\text{kin}}\) of 50 K.
- The outflow parameters are derived with CO (2–1)/(6–5)/(7–6) intensities from the region where the CO (2–1) intensity has an S/N above 3. While the mass is derived by assuming an H\(_2\) density of 10\(^5\) cm\(^{-3}\), the uncertainties are obtained from the masses derived with \(n_{\text{H}_2} = 10^4\) cm\(^{-3}\) (upper limit) and \(n_{\text{H}_2} = 10^6\) cm\(^{-3}\) (lower limit). The pixels with derived kinetic temperature lower than 12 K are removed from the outflow mass estimations.
Yen et al. (2015). If we adopt a dust opacity of \(\kappa_{1.3 \text{ mm}} = 0.01 \text{ cm}^2 \text{ g}^{-1}\) (Ossenkopf & Henning 1994) and assume a dust temperature \(T_{\text{dust}} = 15 \text{ K}\), then we obtain a dust mass of 0.018 \(M_\odot\), around the central objects (0.032 \(M_\odot\) if \(T_{\text{dust}} = 10 \text{ K}\)). However, no elongated structure is found in our continuum map, suggesting that the current resolution is not able to resolve the protostellar disk or a binary system. Thus, it is still unclear whether the 224 GHz dust emission is associated with a protostellar disk, a circumbinary disk, or the inner part of the protostellar envelope.

The JVLA continuum emission at 43 GHz is detected with a FWHM size of \(0.8 \times 0.6\), which is about the size of the beam. The integrated flux density at 43 GHz is \(S_{\text{int}} = 0.158 \pm 0.01 \text{ mJy}\). If we use a graybody approximation \(S_{\nu} \propto \nu^{2+\beta}\), then we obtain an opacity index of \(\beta = 1.3\) from the SMA and JVLA data. However, the angular resolutions and sensitivities of these two data sets are very different. In addition, the extended emission at 224 GHz continuum is likely from more than one point source. Thus, we cannot conclude whether or not these two continuum emissions originate from the same source or what that source may be.

Although the continuum emission at 43 and 224 GHz does not show a clear sign of a binary system, the source sizes provide us clues about the binary separation. The well-detected dust continuum at 224 GHz suggests that the binary separation is at most \(\sim 3''3\) (SMA beam). The JVLA compact emission further implies either a binary separation of less than \(\sim 0.7''\) or a companion that is too faint to be detected at 43 GHz in our current observations. As a result, the binary separation is either approximately less than \(0.7''\) or between \(0.7''\) and \(3''3\) with a faint companion at 43 GHz. Note that the binary separation derived through fitting the wiggling pattern is \(\sim 0.55\), which supports the first possibility.

Figure 1 shows the integrated intensity maps of \(N_2H^+\) (1–0) from Tobin et al. 2012a, \(^{18}\)C\(^{18}\)O (2–1), and \(N_2D^+\) (3–2). \(N_2H^+\) is depleted toward the center as seen in IRAM 04191 (Belloche & André 2004). The depletion region is filled with \(^{18}\)C\(^{18}\)O emission, suggesting that the \(N_2H^+\) depletion is caused by its destruction by CO (Caselli & Ceccarelli 2012). The extended \(^{18}\)C\(^{18}\)O emission toward the source center has a deconvolved FWHM size of \(4''2 \times 2''8\) (\(\sim 500 \text{ au} \times 350 \text{ au}\)) and a peak intensity of \(\sim 1 \text{ Jy beam}^{-1}\). This extent of \(^{18}\)C\(^{18}\)O emission most likely traces the inner region of the envelope. The point-like \(N_2D^+\) source is at a projected distance of \(\sim 325 \text{ au} (2''6)\) from the continuum source. This distance is not inconsistent with the constraints on the binary separation derived from the continuum emission above, but it is inconsistent with the binary separation derived from the analysis of the wiggle pattern in Section 4.1.3. Therefore, the \(N_2D^+\) source is unlikely to be the binary companion. Furthermore, the high deuterium enhancement implies a gas temperature \(\lesssim 20 \text{ K}\), which indicates that the \(N_2D^+\) condensation is unlikely to contain the powering source of the outflow. Therefore, we suggest that the \(N_2D^+\) source is molecular condensation in the core or probably a third small, starless component if it is associated with a continuum source.

4.2.2. Outflow Physical Parameters

We derive the gas temperature \((T_{\text{gas}})\) and column density \((N_{\text{CO}})\) toward the large-scale CO outflow with the single-dish CO (2–1)/(6–5)/(7–6) maps. We smoothed these maps to the same angular resolution (\(11''/2\)) and constructed data cubes with the same spatial and spectral grids (see Sections 2.3 and 2.4). We thus obtain the CO (2–1)/(6–5)/(7–6) intensities at each given position and velocity. Although CO (7–6) is undetected in most regions, the upper limit could still provide constraints on the physical properties. We use the non-LTE radiative transfer code RADEX (van der Tak et al. 2007) to derive the CO column density and gas temperature in each cell \((5'' \times 5'' \times 0.1 \text{ km s}^{-1})\). In addition to the column density and gas temperature, there are two free parameters: the \(H_2\) density \((n_{\text{H}_2})\) and the CO line width. We assume a \(H_2\) density of \(10^5 \text{ cm}^{-3}\), which is about the critical density \((n_{\text{crit}} \sim 1.2 \times 10^5 \text{ cm}^{-3})\) of CO (6–5) (Yang et al. 2010; Yildiz et al. 2013), and we later use \(n_{\text{H}_2} = 10^4 \text{ cm}^{-3}\) and \(n_{\text{H}_2} = 10^3 \text{ cm}^{-3}\) to derive the uncertainties (upper and lower limits). We set the line width (dispersion) as \(\sigma = \Delta V_{\text{chan}} / \sqrt{2\pi}\) such that the "integrated" opacity \(\tau_{\nu} dv = \tau_{\text{peak}} 2\pi \sigma\) is equal to \(\tau_{\text{peak}} \Delta V_{\text{chan}}\), where \(\Delta V_{\text{chan}}\) is the channel width of 0.1 km s\(^{-1}\). This setup enables us to estimate the column density and gas temperature in each channel using the output radiation temperatures of RADEX.

Using the aforementioned method, we derive the column density and gas temperature in each pixel in the channel maps. We adopt an S/N threshold of 3 in CO (2–1) to select the region where the outflow is detected. As a result, we obtain "channel column density" and "channel gas temperature" maps. The column densities are further used to calculate the outflow mass, momentum, force \((F_{\text{CO}})\), kinetic luminosity \((L_{\text{kin}})\), and mass-loss rate \((M)\). The results are provided in Table 3. The upper and lower limits of the column density are calculated with \(H_2\) density assumptions of \(10^3 \text{ cm}^{-3}\) and \(10^4 \text{ cm}^{-3}\), respectively. The lower limits derived with \(n_{\text{H}_2} = 10^3 \text{ cm}^{-3}\) (i.e., under LTE conditions) are very close to the values obtained with \(n_{\text{H}_2} = 10^5 \text{ cm}^{-3}\) which is close to the critical density of CO (6–5). For the upper limits derived under non-LTE conditions \((n_{\text{H}_2} \ll n_{\text{crit}})\), higher column densities are required to reproduce the same observed brightness temperature.
4.2.3. Warm Gas Properties

Mid-J CO transitions are good tracers of warm gas in molecular outflows compared to low-J transitions (Gomez-Ruiz et al. 2013). Since we have found that CO (2–1) and CO (6–5)/(7–6) probe different gas (Section 3.3) and the step 3 summation maps likely better trace the collimated jet (Section 4.1.1), we use the CO (6–5) and (7–6) maps and their step 3 summation maps to study the shocked gas. Figures 11(a) and (b) show the maps of the integrated intensity ratios of CO (7–6) to CO (6–5) and that from the step 3 summation maps, respectively. Excluding the region around the driving sources, the integrated intensity ratios are in the ranges of ~0.3–0.7 in Figure 11(a) and ~0.5–0.9 in Figure 11(b) from where CO (7–6) is detected. This ratio seems to be relatively high in the H2 emission regions. Figure 12 shows the modeled CO (7–6)/(6–5) intensity ratio as a function of H2 density and kinetic temperature from RADEX (van der Tak et al. 2007) at an assumed CO column density of 10^{14} cm^{-2}. In the regions with n_{H2} \lesssim 10^6 cm^{-3}, the intensity ratio is highly dependent on not only the gas temperature but also the H2 density. This implies a model degeneracy because we aim to derive three parameters (T_{gas}, n_{H2}, and N_{CO}) with only two data points (CO 6–5 and 7–6). To break the degeneracies, we adopt the canonical CO abundance of 8 \times 10^{-5} and assume a uniform density distribution. We obtain the following relation:

\[
\left( \frac{N(CO)}{10^{16} \text{ cm}^{-2}} \right) = 0.12 \left( \frac{n_{H2}}{10^5 \text{ cm}^{-3}} \right) \left( \frac{d_{LOS}}{1000 \text{ au}} \right),
\]

where \( d_{LOS} \) is the depth along the line of sight. If we take a jet knot size of a few thousand au as \( d_{LOS} \) as seen in Figure 5, then the warm gas associated with the jet knot has a low H2 density of 10^3–10^4 cm^{-3}. This result hints at a temperature of few hundred Kelvin in the jet knot, which is lower than the hot gas temperature \( T \sim 1000 \text{ K} \) derived from the infrared rotational transitions of H2 by Barsony et al. (2010).

5. DISCUSSION

5.1. Physical Properties of the Outflows

5.1.1. Origin of Warm Gas: CO (6–5)/(7–6)

The origin of warm gas and its heating mechanisms are still debated in the case of low-mass protostars (van Dishoeck et al. 2009; van Kempen et al. 2009b). The possible options are summarized by van Dishoeck et al. (2009) as follows: (1) heating of the collapsing core by the protostellar luminosity within ~100 au; (2) active heating in the shock created by the interaction of the jet/outflow with the envelope; (3) heating by UV photons along the outflow cavity wall (Spaans et al. 1995); (4) heating of a forming protoplanetary disk by accretion shocks (Ceccarelli et al. 2000).

For the large-scale CO (6–5) outflow, options (1) and (4) are excluded since they predict spatially unresolved emission toward the source center. We have decomposed the CO (6–5) outflow into two components (Section 4.1.1): (1) the large-scale structure matching the outflow cavity probed by IRAC 1 and (2) the small-scale structure that lies along the H2 jet emission (Figure 5). The large-scale structure is likely due to heating by UV photons. However, the photon-dominated region created by the central accretion disk is expected to have a size of up to a few thousand au (Spaans et al. 1995; van Kempen et al. 2009a), which is obviously too small to explain the extent of the large-scale CO (6–5) emission (~150″, i.e., ~19,000 au). van Kempen et al. (2009a) suggested that the UV photons can also be produced in the bow shock regions in the outflow if J-shocks are present (Neufeld & Dargarno 1989). This interpretation is supported by the existence of J-shocks suggested by the H2 line study (Barsony et al. 2010).

Although the large-scale CO (6–5) outflow emission mainly originates from UV heating, the knot-like structure matching the H2 jet (Figure 5) is likely contributed by active heating in the shock regions. Using multisolution decomposition, we extracted the small-scale component from CO (6–5) emission (in step 3) and found that it well matched the H2 jet. We conclude from this that these small-scale components may be associated with the jet shocks, but high angular resolution observations are required for confirmation. In addition, these CO (6–5)/(7–6) jet knots preferentially appear after the H2 emission tips (Figure 5). We speculate that CO is dissociated at the bow shock tip where H2 is excited.

The unresolved low-velocity component in CO (7–6) (3.3–4.1 km s^{-1}, see Figure 19) toward the source center can be interpreted by either option (1) or option (4). Our current observations only allow us to constrain an upper limit to the size of the CO (7–6) compact object as <7″\(8 \sim 1000\text{ au} \), the beam size without smoothing). This prevents us from determining the origin of this component. We note that this unresolved low-velocity component is surprisingly not detected in CO (6–5). This raises some doubt concerning the existence of this component. Observations with higher angular resolution and sensitivity are required to solve this issue.

5.1.2. Physical Conditions in the Outflows

We derived the outflow parameters in IRAS 16253 using RADEX (Table 3). These parameters are derived from two data sets with different assumptions: (1) SMA CO (2–1) NE–SW and N–S jets with \( n_{H2} = 10^5 \text{ cm}^{-3} \) and \( T_{kin} = 40 \text{ K} \), and (2)
IRAM CO (2–1) and APEX CO (6–5)/(7–6) maps (hereafter IRAM+APEX) with \( n_H = 10^5 \text{ cm}^{-3} \). The density assumption \( n_H = 10^5 \text{ cm}^{-3} \) implies physical conditions close to LTE. Based on the analysis of IRAM+APEX, we found an outflow temperature of around 40 K and used it to derive the outflow parameters with the SMA CO (2–1) observation.

From IRAM+APEX, we estimate a total outflow mass of \( 14.8 \times 10^{-4} M_\odot \) (the upper and lower limits are derived from \( n_H = 10^3 \) and \( 10^7 \text{ cm}^{-3} \)) which is comparable to that in Stanke et al. (2006). Assuming a gas temperature of 30 K, Stanke et al. (2006) derived an outflow mass of \( 9.6 \times 10^{-4} M_\odot \) from the JCMT CO (3–2) observations in the optically thin limit; since their CO (3–2) observations suffer from optical depth effects, Stanke et al. (2006) scaled the mass to \( 33.7 \times 10^{-4} M_\odot \) by assuming an optical depth correction of \( \tau_{CO} (3-2) = (1 - e^{-\tau_{CO}(3-2)}) \approx 3.5 \). However, this correction of optical depth could be quite uncertain and/or very different from source to source. Our estimate based on multi-transition observations is likely more accurate. Furthermore, based on JCMT CO (3–2) observations, van der Marel et al. (2013) used seven different methods to calculate the outflow forces of IRAS 16253, and our derived force is at about the median of the seven values.

Here, we compare the outflow parameters derived from SMA and IRAM+APEX. Since the mapping areas are different between SMA and IRAM+APEX observations, the outflow mass and momentum cannot be directly compared. Thus, we focus on the outflow force, kinetic luminosity, and mass-loss rate, which should be independent of the mapping areas. The SMA outflow forces and kinetic luminosities are comparable to those from IRAM+APEX if we sum up the contributions from both the NE–SW and N–S jets (see Table 3). We assume that the collimated jets seen with the SMA are driven by the central protostars and the large-scale outflows seen with IRAM+APEX are mostly from the entrained gas and/or outflow cavity wall. Based on the results given in Table 3, we suggest that the collimated jets provide sufficient energy to drive the large-scale outflows.

5.2. Proto-brown Dwarf Binary Candidate

Identifying a proto-BD is very difficult but important for understanding the mechanisms of BD formation (see Section 1). Here, we discuss the parent core mass (Section 5.2.1) and the current stellar mass (Section 5.2.2), and then conclude that IRAS 16253 may have insufficient mass to form a hydrogen-burning star (>0.075 \( M_\odot \)). We further use the outflow force to support this and compare with other currently known young protostars and proto-BD candidates (Section 5.2.3, see also Section 5.3.1).

5.2.1. Parent Core Mass

The growth of an accreting protostar depends on the mass in the parent core. The core mass of IRAS 16253 was estimated in previous studies (0.15 \( M_\odot \) by Barsony et al. 2010; 0.2 \( M_\odot \) by Stanke et al. 2006; 0.5 \( M_\odot \) by Enoch et al. 2008; 0.8 \( M_\odot \) by Tobin et al. 2012). The inconsistencies between these results are due to different assumptions concerning temperatures and core sizes. Although the mass of 0.8 \( M_\odot \) derived by Tobin et al. (2012a) using an 8 \( \mu \text{m} \) extinction map is temperature independent, their core size with a diameter of 0.1 pc (~165") is likely overestimated; this size is much larger than both the size derived by the COMPLETE project (Ridge et al. 2006) from the 850 \( \mu \text{m} \) map (Figure 2(b)) and the FWHM size of 33"×39" estimated by Stanke et al. (2006) from their 1.2 mm map. Since the source is embedded in the \( \rho \) Ophiuchus molecular cloud, a mass estimate considering a larger area can include a lot of material from the ambient cloud that may not participate in the accretion process.

One uncertainty in the core mass comes from the assumed dust temperature; Enoch et al. (2009) derive a mass of 0.51 \( M_\odot \) at 1.1 mm with \( T_{dust} = 15 \text{ K} \) and Stanke et al. (2006) estimate a mass of 0.2 \( M_\odot \) with \( T_{dust} = 20 \text{ K} \) at 1.2 mm. We derive a dust temperature of 17.4 ± 3.8 K using the fluxes at 70, 100, 160, 350, 1100, 1200 \( \mu \text{m} \) from Dunham et al. (2008) by fitting a graybody model. This temperature is consistent with the values of both Enoch et al. (2009) and Stanke et al. (2006) within the uncertainty. Rescaling the masses in Enoch et al. (2009) and Stanke et al. (2006) with a dust temperature of 17.4 K yields 0.41 \( M_\odot \) and 0.24 \( M_\odot \), respectively. In addition, the opacity used for the core mass estimate could be very uncertain. Enoch et al. (2009) adopted the widely used theoretical opacity of Ossenkopf & Henning (1994), which has a deviation that may not be more than a factor of 2. We therefore consider 0.82 \( M_\odot \) as an upper limit of the core mass.

If we assume a star formation efficiency (SFE) of 0.1–0.3 (Tachihara et al. 2002; Jørgensen et al. 2008) and that the two components (see Section 4.1.2) will accrete equal mass in the future, then each component may increase its mass by only <0.04–0.12 \( M_\odot \), which is close to the stellar/BD boundary. Given the very uncertain dust opacity and the unpredictable future accretion (i.e., SFE), it is difficult to determine precisely the final mass of the central stars. However, the very low-mass parent core likely provides material to form only a very low-mass hydrogen-burning binary or a BD binary with one or two substellar objects.

5.2.2. Masses of Central Stars Derived from Orbital Motion

The wiggling pattern caused by orbital motion in the PV diagram (Figure 8) gives us the opportunity to calculate the current mass of the central star(s) in IRAS 16253 using Equation (6). We derive an orbital period \( P_{\text{orb}} \) of ~3300 years from the orbital velocity and radius in Table 2. Taking the binary separation \( a = R_1 + R_2 = 0.555 \text{ (69 au)} \), we obtain current stellar masses of 0.026 \( M_\odot \) and 0.006 \( M_\odot \). The mass ratio comes from \( M_1 V_{\text{orb},1} = M_2 V_{\text{orb},2} \). This result, together with the future accretion (<0.04–0.12 \( M_\odot \); see Section 5.2.1), implies that IRAS 16253 will form a very low-mass binary system or a BD binary system with at least one BD. Since IRAS 16253 is located in an isolated environment, our results imply that BFs can form in a manner similar to normal low-mass stars.

Two caveats should be mentioned. First, the results obtained from the fit to the PV diagrams (Table 2) depend on the inclination angle. We derive the total mass of the central stars as 0.01 \( M_\odot \) with \( \theta_{\text{inc}} = 10^\circ \) and 0.04 \( M_\odot \) with \( \theta_{\text{inc}} = 30^\circ \). Thus, although the inclination angle affects the estimate of the central mass, it does not change the conclusion that IRAS 16253 is probably a proto-BD binary system. Second, the sinusoidal pattern in the PV diagram of the N–S jet (Figure 8) is not as well fit by the model as the NE–SW jet, implying that \( R_2 \) and \( V_{\text{orb},2} \) are uncertain. However, this would not affect the orbital period \( P_{\text{orb}} \) which is obtained from \( R_1 \) and \( V_{\text{orb},1} \) and is independent of \( R_2 \) and \( V_{\text{orb},2} \); we can also replace \( \frac{V_{\text{orb},1}}{R_1} \) in
Figure 13. Relation between bolometric luminosity and outflow force. The figure is reproduced from Figure 7 in Palau et al. (2014) with IRAS 16253 (brown star) added for comparison. Blue, red, and green points represent YSOs, FHSC, and VeLLOs; however, we label brown dwarf candidates as brown points which are also VeLLOs. Outflow forces measured by interferometers and single dishes are labeled with triangles and circles, respectively. The arrows indicate upper limits.

Equation (4) by \( \frac{2\pi f}{\lambda_{\text{orb}}} \), where \( \lambda_{\text{orb}} \) is the spatial period of the jet due to the orbital motion (see Equation (3)), such that the period can be derived with \( f_{\text{orb}} = \lambda_{\text{orb}} / V_{\text{jet}} \cos(\alpha') \). Taking the orbital period, we obtain the total mass of the central stars as a function of \( a \) using Equation (6):

\[
M_{\text{tot}} = \frac{4\pi^2}{GP_{\text{orb}}} a^3.
\]

The JVLA continuum map hints that the binary separation is less than 0.05, although we cannot exclude the possibility that the companion is too faint to be detected at 43 GHz. If we take 0.05 as the upper limit of the separation, then the total mass of the central stars would be less than 0.032 \( M_\odot \). Given the future accretion \(<0.04–0.12 M_\odot\) (for each component, see Section 5.2.1), IRAS 16253 will form a very low-mass binary system which may contain BDs.

5.2.3. Implication of the Outflow Force for a Proto-BD

The weak outflow force in IRAS 16253 also hints at IRAS 16253 being a proto-BD. A correlation between the outflow force and bolometric luminosity \( L_{\text{bol}} \) has been found and investigated in the past two decades (Bontemps et al. 1996; Wu et al. 2004). Palau et al. (2014) compared the proto-BD candidate IC 348-SMM2E with VeLLOs (Di Francesco et al. 2007), First Hydrostatic Cores (FHSCs, Larson 1969), and normal protostars in the \( F_{\text{C}} - L_{\text{bol}} \) plot, in which VeLLOs could be very low-mass protostars or proto-BDs, and FHSCs are believed to be the youngest protostars (see Table 6 in Palau et al. 2014 and references therein). We include IRAS 16253 in this plot (Figure 13) and further highlight four VeLLOs which are considered as proto-BDs (L1014-IRS, Huard et al. 2006, Bourke et al. 2005; L328, Lee et al. 2009, 2013; L1148-IRS, Kauffmann et al. 2011; IC 348-SMM2E, Palau et al. 2014). IRAS 16253 is located between these proto-BD candidates and VeLLOs. However, IRAS 16253 is the only source which is likely to be a binary system among these proto-BD candidates. Thus, the outflow force and the bolometric luminosity should be considered as upper limits because they are contributed by two objects.

5.3. Mass Accretion

5.3.1. Estimate of Mass Accretion Rate from Outflow Force

The outflow force is usually used to estimate the mass accretion rate and accretion luminosity \( L_{\text{acc}} \) in order to understand the nature of VeLLOs (Dunham et al. 2010a; Lee et al. 2013; Takahashi et al. 2013). Here, we follow the method for estimating the accretion rate from Dunham et al. (2010a) and Lee et al. (2013). Assuming that the gravitational energy released through a protostellar jet/outflow is correlated with mass accretion onto the protostar, the mass accretion rate \( (M_{\text{acc}}) \) can be represented as

\[
M_{\text{acc}} = \frac{1}{f_{\text{ent}}} \frac{M_{\text{W}}}{V_{\text{W}}} f_{\text{out}},
\]

where \( f_{\text{ent}} \) is the entrainment efficiency, \( M_{\text{W}} \) is the mass-loss rate, and \( V_{\text{W}} \) is the jet velocity (Bontemps et al. 1996). We adopt \( f_{\text{ent}} = 0.1 \), \( M_{\text{W}} / M_{\text{acc}} = 0.1 \), and \( V_{\text{W}} = 150 \text{ km s}^{-1} \) (André et al. 1999; Dunham et al. 2010a), and obtain a mass accretion rate of \( 4.7 \times 10^{-7} M_\odot \text{ yr}^{-1} \) for IRAS 16253. Assuming 10% mass loss through a jet or wind (Bontemps et al. 1996), we derive the accreted mass during the Class 0 lifetime of \( \sim 0.16 \text{ Myr} \) (André et al. 2000, p. 59; Evans et al. 2009) to be \( \sim 0.068 M_\odot \). If a star accretes half of its mass at the Class 0 stage, then IRAS 16253 could only reach a terminal total mass of \( \sim 0.14 M_\odot \) (including two components). This result may be considered as an upper limit because the mass accretion rate is believed to decrease as the core evolves (Bontemps et al. 1996), and IRAS 16253, with a bolometric temperature of 27 K, is likely a very young Class 0 object (Hsieh et al. 2015). This result is consistent with the conclusions in Sections 5.2.1 and 5.2.2. We note that the jet velocities of proto-BDs were recently found to be \( 50–100 \text{ km s}^{-1} \) (Morata et al. 2015), which would yield an increase in the mass accretion rate and terminal total mass by a factor of \( 1.5–3 \), i.e., a mass of \( 0.21–0.42 M_\odot \). However, given the parent core mass of \( <0.82 M_\odot \), the higher value would imply an SFE of 0.5, which is unlikely.

Because the accretion luminosity is one of the crucial parameters for understanding the low luminosity of VeLLOs, we calculate the accretion luminosity \( L_{\text{acc}} \) using

\[
L_{\text{acc}} = \frac{GM_{\text{acc}} M_{\text{acc}}}{R},
\]

where \( G \) is the gravitational constant, \( M_{\text{acc}} \) is the accreted mass \( (M_{\text{acc}} \times \tau_{\text{dyn}}) \), and \( R \) is the protostellar radius \( (3 R_\odot) \). The resulting accretion luminosity is \( \sim 0.03 L_\odot \). Given the uncertainties on \( L_{\text{acc}} \), this value is comparable to the internal luminosity of \( 0.08–0.09 L_\odot \) (Dunham et al. 2008).

5.3.2. Probe of Episodic Accretion

Episodic accretion has been proposed (Dunham et al. 2010b; Dunham & Vorobyov 2012; Jørgensen et al. 2015) as a solution to the long-standing luminosity problem, namely, that the observed bolometric luminosities and mass accretion rates in protostars are much lower than expected (Kenyon...
et al. 1990). The discovery of VeLLOs has further exacerbated the luminosity problem and VeLLOs have become important for studying it. In episodic accretion models, a protostellar system spends most of its time in a quiescent accretion stage with accretion bursts occasionally occurring to deliver material onto the central protostar (Kenyon & Hartmann 1995; Lee 2007; Dunham et al. 2010b; Dunham & Vorobyov 2012; Jørgensen et al. 2015). This behavior leads to protostars having a low luminosity for most of the time but still accreting sufficient mass.

Jørgensen et al. (2015) proposed that a recent accretion burst could be probed by comparing the observed extent of C\textsuperscript{18}O emission with the predicted extent given by the current source luminosity. An accretion burst would enhance the luminosity (i.e., accretion luminosity \(L_{\text{acc}}\)), heating the parent core and shifting the CO freeze-out/sublimation boundary to a larger radius. After a burst, CO would take a long time to refreeze-out onto the dust surfaces (\(10^3\)–\(10^4\) year; Visser et al. 2015) while the accretion luminosity decays. The C\textsuperscript{18}O extent in IRAS 16253, with a radius of \(\sim 210\) au (\(\sqrt{4/2 \times 2 \pi / 8} = 1\) s, see Section 4.2.1), is significantly larger than the expected radius of \(\sim 100\) au considering the bolometric luminosity of 0.25 \(L_{\odot}\) (see Figure 4 in Jørgensen et al. 2015); the expected radius is where the temperature reaches the CO sublimation region (20–30 K) produced by heating from the central object. The luminosity needed to reproduce the C\textsuperscript{18}O extent is a factor of \(\sim 4\) higher than the current bolometric luminosity of IRAS 16253. Because the C\textsuperscript{18}O emission shows no clear correlation with jets on large scales (Figure 1), we suggest that the C\textsuperscript{18}O emission is associated with the dense inner region of the envelope, similar to the sources in Jørgensen et al. (2015). As a result, IRAS 16253 is likely in a post-burst stage (or has undergone a recent accretion burst) of the episodic accretion process.

We set a model with one accretion burst that occurred during the jet dynamical time (1.3 \times 10^4 year) in order to examine whether or not we can detect the occurrence of a burst based on the jet locus. In this model, we assume that a burst occurred at \(-6000\) years and the mass linearly increased within 1000 years (ending at \(-5000\) years). Our model predicts a transition in the jet locus due to the accretion burst: the trajectory changes abruptly in Figure 10(c), with rapid variations in amplitude and period. Because our model simply considers Kepler’s law, the path at the transition phase may not be exactly true. Nevertheless, we find that the wiggling patterns are very different before and after an accretion burst. Therefore, we suggest that with additional high spatial and spectral resolution data covering the whole jet, modeling the jet wiggling pattern could help to identify the accretion process (episodic or continuous) and assess whether accretion bursts have occurred.

6. SUMMARY

For the first time, we have identified a proto-BD binary system candidate based on its dynamics. Based on multi-transition CO (2–1/6–5/7–6) observations from single dishes (IRAM 30 m and APEX) and an interferometer (SMA), we studied in detail the dynamical and physical properties of the protostellar jets driven by IRAS 16253. The “S-shaped” jet detected in H\textsubscript{2} and CO (6–5) suggests that IRAS 16253 hosts a close binary system. The SMA CO (2–1) data further reveal the jet wiggling caused by the orbital motion in the PV diagram, which allows us to probe the dynamics of the central binary system. Furthermore, we use the multi-transition CO data to derive the gas temperature and column density of the outflows. As a result, we obtain the outflow mass, momentum, and force of IRAS 16253. We also find that the small-scale emission of the mid-J CO transitions matches the H\textsubscript{2} emission and probes the shocked gas while the low-J CO transition does not. Here, we summarize the properties of (1) the proto-BD binary candidate IRAS 16253 and (2) its jets/outflows.

1. The proto-brown dwarf binary candidate IRAS 16253.
   a. Using the jet-wiggle model, we derive the current total mass of the binary system as 0.032 \pm 0.003 \(M_{\odot}\). The low parent core mass (\(< 0.8 \, M_{\odot}\)) further suggests that IRAS 16253 will form a very low-mass binary or a BD binary in the future.
   b. The low outflow force implies a very low mass accretion rate in IRAS 16253 in the main accretion phase, suggesting that it will probably form substellar objects. The outflow force versus bolometric luminosity plot also hints at IRAS 16253 being a proto-BD binary candidate.
   c. The extended C\textsuperscript{18}O emission, together with the N\textsubscript{2}H\textsuperscript{+} depletion, implies that IRAS 16253 has experienced an accretion burst in the last \(\sim 10^4\) year, which is approximately the dynamical age of the protostellar jet.
   d. Since IRAS 16253 is located in an isolated environment, our result supports a scenario in which BDs form through fragmentation and collapse similar to normal hydrogen-burning stars.

2. The jets/outflows driven by IRAS 16253.
   a. The CO (2–1) emission from IRAM 30 m primarily traces the entrained gas and/or outflow cavity. The CO (6–5) emission can be decomposed into two components: (1) the large-scale outflow cavity wall presumably heated by UV photons from a jet-driven bow shock and (2) the high-velocity shocked gas heated by the interaction of the jet and the envelope.
   b. The outflow energies and the forces derived from the small-scale SMA CO (2–1) jets are comparable to those of the large-scale IRAM CO (2–1) outflows, suggesting that the entrained gas can be driven by the collimated jets.
   c. We modeled the jet wiggling pattern caused by the orbital motion in the position–velocity diagram for a protostellar jet driven by a binary system. The model could be used to trace the history of the binary formation including the orbital evolution and accretion process.

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APPENDIX

ORIGINAL MAPS AND CHANNEL MAPS

To study the molecular outflows, we remove the large-scale CO emission in our single-dish observations using a multiresolution analysis (see Section 4.1.1, Belloche et al. 2011) because they are mostly contributed by the molecular cloud and core. This analysis decomposes the intensity maps into summation maps (small-scale) and smooth maps (large-scale) which correspond to the outflow and cloud emissions, respectively. We apply this analysis to our CO (2–1)/(6–5)/(7–6) channel maps and all of the analyses performed in this paper are based on the small-scale outflow maps; the outflow properties are derived from the step 4 CO (2–1), step 5 CO (6–5), and step 4 CO (7–6) summation maps which correspond to the structures at scales less than 17 pixels, 31 pixels, and 17 pixels with a pixel size of 5″. We show the integrated intensity maps of the input map and the output maps (summation maps and smooth maps) in Figure 14. The channel maps of the summation maps and smooth maps are shown in Figures 15–20.

Figure 14. Comparison of integrated intensity maps before and after removing large-scale structures. The left, middle, and right panels represent CO (2–1), (6–5), and (7–6) maps, respectively, and the top, middle, and bottom panels represent the summation, smooth, and input maps, respectively (see Section 4.1.1). The blueshifted (right) and redshifted (left) integrated maps have the same velocity ranges as in Figure 3.

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Figure 15. IRAM CO (2–1) channel maps after filtering the large-scale emission. These channel maps were processed through the multiresolution analysis of Belloche et al. (2011) and represent the step 4 summation maps. The contour levels are $-10$, $-5$, $-3$, $3$, $5$, $10$, $20$, and $30$ $\sigma$ with an rms noise level of $\sigma = 0.26$ K. The red star indicates the position of the infrared source.

Figure 16. IRAM CO (2–1) channel maps of large-scale emission which is filtered in Figure 15. The contour levels are the same as those of Figure 15.
Figure 17. APEX CO (6–5) channel maps after filtering the large-scale emission. These channel maps were processed through the multiresolution analysis of Belloche et al. (2011) and represent the step 5 summation maps. The contour levels are $-10$, $-5$, $-3$, $3$, $5$, $10$, and $20\sigma$ with an rms noise level of $\sigma = 0.28$ K.

Figure 18. APEX CO (6–5) channel maps of large-scale emission which is filtered in Figure 17. The contour levels are the same as those of Figure 17.
Figure 19. APEX CO (7–6) channel maps after filtering the large-scale emission. These channel maps were processed through the multiresolution analysis of Belloche et al. (2011) and represent the step 4 summation maps. The contour levels are 3 and 5σ with an rms noise level of σ = 0.57 K.

Figure 20. APEX CO (7–6) channel maps of large-scale emission which is filtered in Figure 19. The contour levels are the same as those of Figure 19.
