CHARACTERIZATION OF MOLECULAR OUTFLOWS IN THE SUBSTELLAR DOMAIN

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ABSTRACT

We report here our latest search for molecular outflows from young brown dwarfs and very low-mass stars in nearby star-forming regions. We have observed three sources in Taurus with the Submillimeter Array and the Combined Array for Research in Millimeter-wave Astronomy at 230 GHz frequency to search for CO J = 2 → 1 outflows. We obtain a tentative detection of a redshifted and extended gas lobe at about 10 arcsec from the source GM Tau, a young brown dwarf in Taurus with an estimated mass of 73 M_J, which is right below the hydrogen-burning limit. No blueshifted emission around the brown dwarf position is detected. The redshifted gas lobe that is elongated in the northeast direction suggests a possible bipolar outflow from the source with a position angle of about 36°. Assuming that the redshifted emission is outflow emission from GM Tau, we then estimate a molecular outflow mass in the range from 1.9 × 10^{-6} M_⊙ to 2.9 × 10^{-5} M_⊙ and an outflow mass-loss rate from 2.7 × 10^{-9} M_⊙ yr^{-1} to 4.1 × 10^{-8} M_⊙ yr^{-1}. These values are comparable to those we have observed in the young brown dwarf ISO-Oph 102 of 60 M_J in ρ Ophiuchi and the very low-mass star MHO 5 of 90 M_J in Taurus. Our results suggest that the outflow process in very low-mass objects is episodic with a duration of a few thousand years and the outflow rate of active episodes does not significantly change for different stages of the formation process of very low-mass objects. This may provide us with important implications that clarify the formation process of brown dwarfs.

Key words: brown dwarfs – ISM: individual objects (GM Tau, 2MASS J04141188+2811535, 2MASS J04381486+2611399) – ISM: jets and outflows – stars: formation – stars: low-mass – techniques: interferometric

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1. INTRODUCTION

Over the last 19 years, observations of the statistical properties, such as the initial mass function, velocity dispersion, multiplicity, accretion, and jets (see Luhman et al. 2007 and references therein), of brown dwarfs (BDs; 13–75 M_J) and very low-mass stars (VLMS) in nearby star-forming regions have shown that all these properties of BDs and VLMS stars (hereafter VLM objects) form a continuum with those of low-mass stars. These observations therefore strongly support the starlike models (see Whitworth et al. 2007 and references therein), wherein VLM objects form in the same manner as low-mass stars. While the starlike models predict that pre-BD cores, which are produced by turbulent fragmentation of molecular clouds (Padoan & Nordlund 2004) or gravitational fragmentation (Bonnell et al. 2008), are dense enough to be gravitationally unstable, it is still unclear how the physical processes of BD formation occur at later stages, such as at class 0, I, and II.

Since bipolar molecular outflows, which are ambient gas swept up by an underlying jet/wind (see Bachiller 1996; McKee & Ostriker 2007 and references therein), are a basic component of the star formation process, studying the molecular outflow properties will therefore help us understand the BD formation mechanism. In the last few years, we have reported the first detections of bipolar molecular outflows from the class II BD ISO-Oph 102 in ρ Ophiuchi (Phan-Bao et al. 2008) and the class II VLM star MHO 5 in Taurus (Phan-Bao et al. 2011). Our estimated values of outflow mass and mass loss rate in these VLM objects are over an order of magnitude smaller than the typical values in low-mass stars. These results have implied that the outflow process in VLM objects is a scaled-down version of that in low-mass stars. Our detections have also provided strong observational constraints such as velocity, size, mass, and mass-loss rate of the outflow process for the simulation of BD formation (e.g., Machida et al. 2009). Although the molecular outflow process holds important clues to BD formation, only four detections of molecular outflows in the substellar domain have been reported so far: two molecular outflows from class 0/I proto BD and VLM candidates (L1014-IRS: Bourke et al. 2005; L1148-IRS: Kauffmann et al. 2011), one from a class II BD (ISO-Oph 102, ∼60 M_J; Phan-Bao et al. 2008), and one from a class II VLM star (MHO 5, ∼90 M_J; Phan-Bao et al. 2011).

In this paper, we present our millimeter observations of three class II BDs in Taurus. Section 2 presents our sample. Section 3 reports our millimeter observations and the data reduction. Section 4 presents the observational results. Section 5 discusses the outflow process and the formation mechanism of VLM objects. Section 6 summarizes our results.

2. SAMPLE SELECTION

Our sample consists of eight targets in ρ Ophiuchi and Taurus. All of them are class II VLM objects. Five of them were reported in Phan-Bao et al. (2008, 2011).

In this paper, we present the observations of three remaining targets in Taurus (147 pc; see Loinard et al. 2007): GM Tau, 2MASS J041411.88+2811535 (hereafter 2M 0414) and
2MASS J043814.86+2611399 (hereafter 2M 0438). GM Tau was identified as a pre-main-sequence star Briceño et al. (1993), in the dark cloud HCL 2 or TMC 1 (e.g., Goldsmith et al. 2008) according to its position. The source was then spectroscopically classified as an M6.5 dwarf with an estimated mass of $\sim 73 M_J$ (White & Basri 2003). GM Tau shows an obvious P Cygni profile (see Figure 4 in White & Basri 2003) with blueshifted absorption components superposed on the H$\alpha$ accretion emission profile, which strongly indicates a mass-loss process as seen in higher-mass T Tauri stars. 2M 0414 is an M6.25 dwarf of $70 M_J$ (Luhman 2004; Muzerolle et al. 2005), the source lies in the dark cloud LDN 1495 (e.g., Goldsmith et al. 2008) according to its position. The H$\alpha$ emission of 2M 0414 also shows a clear P Cygni profile (see Figure 4 in Muzerolle et al. 2005), implying a mass-loss process occurring in the source. 2M 0438 is an M7.25 dwarf of 70 $M_J$ (Luhman 2004; Muzerolle et al. 2005), which lies in the same dark cloud as GM Tau. This BD exhibits strong forbidden emission lines (FELs; Luhman 2004) as seen in MHO 5 that could be associated with outflow activities. They are therefore excellent targets for our search for molecular outflows in VLM objects. One should note that no detection of any cores associated with the three sources has been reported so far.

### 3. OBSERVATIONS AND DATA REDUCTION

We observed GM Tau with the Submillimeter Array (SMA), and 2M 0414 and 2M 0438 with Combined Array for Research in Millimeter-wave Astronomy (CARMA). The observing log of the three young BDs is given in Table 1.

#### 3.1. SMA Observations

The SMA$^6$ receiver band at 230 GHz (see Ho et al. 2004) was used for the observations of GM Tau on 2010 October 26. Zenith opacities at 225 GHz were typically in the range 0.1–0.16. Both 4 GHz wide sidebands, which are separated by 8 GHz, were used. The SMA correlator was configured with a high spectral resolution of 0.2 MHz ($\sim 0.27$ km s$^{-1}$) per channel for $^{12}$CO, $^{13}$CO, and $^{18}$O $J = 2 \rightarrow 1$ lines. For the remainder of each sideband, we set up a lower resolution of 3.25 MHz per channel. We used quasars 3C 111 and 3C 273 for gain and passband calibration of GM Tau, respectively. Uranus was observed for flux calibration for the target. The uncertainty in the absolute flux calibration is $\sim 10\%$.

We reduced and further analyzed the data with the MIR software package and the MIRIAD package adapted for the SMA, respectively. All eight SMA antennas were operated in the compact configuration, resulting in a synthesized beam of $3'05 \times 2'82$ with a position angle of 61$^\circ$ (natural weighting). The FWHM of the primary beam is about 50$^\prime$ at the observed frequencies. The rms sensitivity was $\sim 1$ mJy for the continuum and $\sim 0.15$ Jy beam$^{-1}$ per channel for the line data (Table 1).

#### 3.2. CARMA Observations

We observed the two BDs 2M 0414 and 2M 0438 with CARMA at 230 GHz in 2010 August. All six 10.4 m and nine 6.1 m antennas were operated in the D configuration. Zenith opacities at 227 GHz were in the range 0.21–0.3 and 0.23–0.27 for 2M 0414 and 2M 0438, respectively. All eight 500 MHz wide bands (a maximum bandwidth of 4 GHz per sideband), which may be positioned independently with the IF bandwidth, were used with different spectral resolutions for the $^{12}$CO $J = 2 \rightarrow 1$ line. The eight bands were set up in the following modes with the 2-BIT level: 8 MHz, 31 MHz, and 62 MHz with 383 channels per band; 125 MHz, 250 MHz, and 500 MHz with 191, 199, and 95 channels per band, respectively. These modes give a wide range of spectral resolutions from 0.03 to 6.8 km s$^{-1}$ at 230 GHz. We observed quasar 3C 111 for gain calibration, 3C 84 and 3C 103 at 230 GHz. We observed quasar 3C 84 and 3C 103 at 230 GHz.

#### 4. RESULTS

##### 4.1. 2M 0414 and 2M 0438

2M 0414 and 2M 0438 are strong accretors (see Table 3 and references therein). While the H$\alpha$ emission with an obvious P Cygni profile observed in 2M 0414 (Muzerolle et al. 2005) indicates an outflow process and the presence of FELs in 2M 0438 (Luhman 2004) suggests outflow activity, our carbon monoxide (CO $J = 2 \rightarrow 1$) maps from CARMA data do not reveal any outflows from 2M 0414 and 2M 0438. The non-detection of molecular outflows in these two BDs indicates three possible scenarios as discussed in Phan-Bao et al. (2011): (1) the outflow process has already stopped; (2) there is not much gas surrounding the sources; or (3) the outflow process in these BDs is too weak to be detectable at the millimeter wavelengths.

For the case of 2M 0414, the outflow process has clearly been indicated in its H$\alpha$ emission, therefore, the first scenario should be ruled out. As the source is located in the dense region of $^{12}$CO and $^{13}$CO $J = 1 \rightarrow 0$ of LDN 1495 (see Figure 4 in Goldsmith et al. 2008), the second scenario is thus unlikely in this case. Finally, the bolometric luminosity of 2M 0414 is 0.015 $L_\odot$ (Luhman 2004), about three times less luminous than

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that of GM Tau (0.047 $L_\odot$, Luhman 2004). If we assume that the outflow force versus bolometric luminosity correlation of proto stars (e.g., Takahashi & Ho 2012) is applicable for young BDs, this thus indicates that the outflow force of 2M 0414 would be weaker (i.e., weaker molecular outflow emission) than that of GM Tau. As a possible outflow from GM Tau is marginally detected (see Section 4.2), the third scenario would therefore be a reasonable explanation for the non-detection of outflows from 2M 0414.

For the case of 2M 0438, the source is also located in the dense region (see Figure 4 in Goldsmith et al. 2008) and it is close to GM Tau (at a distance of only $\sim$2.8$\prime$), the second scenario is thus very unlikely. The FELs may be associated with outflow or accretion activities, the first scenario is thus still possible. One should note that the bolometric luminosity of 2M 0438 is very low (0.0018 $L_\odot$, Luhman 2004), therefore, the outflow force is expected to be much less powerful than that of any class II BDs with molecular outflows detected so far. So, the first and the third scenarios are both possible for 2M 0438.

One should also note that we did not detect the dust continuum emission from 2M 0414 and 2M 0438 with an upper limit of about 1$\sigma$ (1$\sigma$ = 1.4 mJy for 2M 0438 and 1.1 mJy for 2M 0414). Our measurements are comparable within error bars to those reported in Scholz et al. (2006), 0.91 ± 0.65 mJy for 2M 0414 and 2.29 ± 0.75 mJy for 2M 0438.

4.2. GM Tau

GM Tau is also a strong accretor with a mass accretion rate stronger than that of 2M 0414 and 2M 0438 (Table 3). Its obvious P Cygni profile of H$\alpha$ emission strongly indicates the outflow process occurring in the BD.

The systemic velocity of GM Tau has not been available in the literature so far. To measure the systemic velocity of the BD, we extract a $^{13}$CO $J = 1 \rightarrow 0$ spectrum toward GM Tau with the reprocessed FCRAO Taurus survey data from Qian et al. (2012). The FWHM of the $^{13}$CO line is about 2.2 km s$^{-1}$ (Figure 1), which is better described by two Gaussian components with peak velocities of 5.5 ± 0.3 km s$^{-1}$ and 6.5 ± 0.3 km s$^{-1}$, respectively. The large-scale velocity gradient of $^{13}$CO seems to roughly follow a Larson’s law-type power-law with respect to spatial scales (see Figure 18 in Qian et al. 2012). The FWHM of the FCRAO primary beam is about 50$''$. Within 50$''$, it is thus normal in Taurus to have gas components moving at 0.5–1 km s$^{-1}$ with respect to each other. The FCRAO data therefore suggests the systemic velocity of GM Tau to be in the range from 5.5 to 6.5 km s$^{-1}$. We thus take an average value of 6.0 km s$^{-1}$ for the systemic velocity of the BD. Figure 2 presents the integrated intensity in the CO $J = 2 \rightarrow 1$ emission toward GM Tau. Our map reveals only a redshifted (~6.6–7.2 km s$^{-1}$) CO gas lobe around the BD position. No blueshifted emission is detected. It is therefore difficult to confirm that the redshifted lobe is outflow emission from GM Tau. However, the gas lobe is elongated in the northeast direction of the BD position, with a position angle of about 36$\circ$. This suggests that the redshifted emission is possibly outflow emission from GM Tau. One should note that the redshifted component is marginally detected at only 4$\sigma$. Therefore, if it really comes from an outflow of the BD, the detection of the CO outflow from GM Tau should be considered as a tentative detection. Our previous detections (Phan-Bao et al. 2008, 2011) have shown that the molecular outflow in the VLM objects is bipolar as seen in low-mass stars and the intensity of the outflow emission differs significantly between the redshifted and blueshifted components. Therefore, the non-detection of blueshifted outflow emission from GM Tau is probably due to the emission being too weak to be detected with SMA. The redshifted emission being brighter than the blueshifted emission implies that the redshifted jet propagates into denser gas than the blueshifted jet, leading to a larger swept up mass of CO gas (i.e., stronger molecular outflow emission). Deeper observations are needed to confirm this scenario.

If the detected redshifted gas lobe is a component of outflows from GM Tau, we then follow the standard manner (Cabrit & Bertout 1990; André et al. 1999) as used in previous papers (Phan-Bao et al. 2008, 2011) to calculate the outflow properties. The size of the redshifted CO gas lobe is about 5$''$ corresponding to ~700 AU in length (see Figure 2). We assume a value of 20 K for the excitation temperature, and then derive a lower limit to the outflow mass $M_{\text{out}} \sim 1.9 \times 10^{-6} M_\odot$. The correction factors due to optical depth and missing flux for the outflow mass of GM Tau are uncertain. However, the typical values of optical depths for class II objects in Taurus are from 1 to 5 (Levreault 1988a). As GM Tau lies in the densest part of HCL 2 (see Figure 4 of Goldsmith et al. 2008), it is therefore reasonable to assume an optical depth of five for the case of GM Tau. If a missing flux factor of three for SMA (Bourke et al. 2005) is applicable here, then we obtain an upper limit to the outflow mass of $\sim 2.9 \times 10^{-5} M_\odot$.

The maximum outflow velocity $v_{\text{max}}$ can be computed from the observed maximum outflow velocity and the outflow inclination. The observed maximum outflow velocity is about 1.2 km s$^{-1}$. Based on optical, near-infrared, and infrared data, Riaz et al. (2012) performed disk modeling for GM Tau with a circumstellar geometry consisting of a rotationally flattened infalling envelope, bipolar cavities, and a flared accretion disk in hydrostatic equilibrium. Their best-fitting model spectral energy distribution was obtained with the disk’s inclination angle between 70$\circ$ and 80$\circ$. We therefore use an average value of 75$\circ$ for the outflow inclination (the angle between the outflow axis and the line of sight). From the observed maximum outflow velocity of 1.2 km s$^{-1}$ and the outflow inclination angle $i = 75^\circ$, we derive the maximum outflow velocity $v_{\text{max}} = 4.6 \text{ km s}^{-1}$.
We then use this value to compute upper limit values for the kinematic and dynamic parameters. We find that the momentum is $P = 8.7 \times 10^{-6} M_\odot \text{ km s}^{-1}$ and the energy is $E = 2.0 \times 10^{-5} M_\odot \text{ km}^2 \text{ s}^{-2}$. From the outflow size of $\sim$700 AU and the observed maximum outflow velocity of 1.2 km s$^{-1}$, we derive a dynamical time $t_{\text{dyn}}$ for GM Tau of about 700 yr (with a correction for the outflow inclination). With this dynamical time value, we then find the force $F = 1.2 \times 10^{-8} M_\odot \text{ km s}^{-1} \text{ yr}^{-1}$ and the mechanical luminosity $L = 4.7 \times 10^{-6} L_\odot$, where $L_\odot$ is the solar luminosity. If we apply a correction for the optical depth factor of five and the missing flux factor of three for SMA, these upper limit values will increase by a factor of fifteen. Lower limits to these parameters could be estimated by using the outflow mass in each velocity channel and the space velocity of the outflow, which is assumed to be equal to the radial velocity of that channel, as if the gas was moving along the line of sight (Cabrit & Bertout 1990). This could be done for observations with good signal-to-noise ratio. However, as our detection levels of outflows in each velocity channel are rather low, we do not estimate these lower limits.

The mass-loss rate of molecular outflows can be computed by dividing the outflow mass by the dynamical time of the outflow. However, the estimated dynamical time $t_{\text{dyn}} \sim 700$ yr for the outflow from GM Tau is over two orders of magnitude smaller than the age of VLM objects in Taurus, expected to be from a few $10^5$ yr to a few Myr (Muzerolle et al. 2003; White & Basri 2003). Therefore, the correction factor of about 10 for the outflow dynamical time of young low-mass stars (Parker et al. 1991) may be not valid here. This value for VLM objects should be over 100 (see further discussion in Section 5.1). Without correction applied for the outflow dynamical time and using the lower and upper values of the outflow mass, we directly derive the lower and upper limits to the mass-loss rate of molecular outflows $M_{\text{mol}} = M_{\text{out}} / t_{\text{dyn}}$ to be $2.7 \times 10^{-9} M_\odot \text{ yr}^{-1}$ and $4.1 \times 10^{-8} M_\odot \text{ yr}^{-1}$, respectively.

We now consider the possibility that the detected redshifted emission might be due to gravitationally bound motion and not outflow emission. For gravitationally bound motion, an outflow size $l = 700$ AU with a velocity $v = 4.6$ km s$^{-1}$ would require an enclosed mass of $\gtrsim 8.4 M_\odot$ ($M \geq v^2 l / 2 G$; see Lada 1985). If we assume that the densest cores in Taurus have been detected by Onishi et al. (2002, see their Table 2), then we derive a possible largest mass of $\sim 0.003 M_\odot$ for a core 700 AU in diameter. In addition, we also estimate an upper limit to the mass of a core of 700 AU using the gas density around the GM Tau position, which is estimated from the FCRAO observations (Qian et al. 2012). The line intensity ratio between $^{13}$CO $J = 1 \rightarrow 0$ and $^{13}$CO $J = 1 \rightarrow 1$ is much smaller than the corresponding isotopic ratio, thus it is safe to assume that the $^{13}$CO line is optically thick. We then derive the gas excitation temperature of about 10 K based on the peak antenna temperature of $^{12}$CO. The $^{13}$CO opacity, and in turn the gas column density, can then be derived by assuming a $[^{13}$CO]/[H$_2$] abundance ratio of $1.7 \times 10^{-5}$ (Frerking et al. 1982). The resulting H$_2$ column density...
5. MOLECULAR OUTFLOWS FROM VLM OBJECTS

5.1. Molecular Outflow Properties

So far, we have observed eight VLM objects and detected three of them with CO molecular outflows: ISO-Oph 102 in ρ Ophiuchi (Phan-Bao et al. 2008), MHO 5 (Phan-Bao et al. 2011), and GM Tau (this paper) in Taurus. The molecular outflows from these three sources show similar molecular outflow properties: a small scale of 600–1000 AU, a low velocity of ≲5 km s⁻¹ (with a correction of outflow inclination), a tiny outflow mass of 10⁻⁵–10⁻⁴ M⊙, and a low mass-loss rate of 10⁻⁹–10⁻⁷ M⊙ yr⁻¹. Table 2 lists these properties for each source. Our molecular outflow mass estimates in VLM objects are smaller than the typical values 0.1–0.7 M⊙ of class II low-mass stars (G and K spectral types; see Levreault 1988b and references therein) by an order of magnitude.

To estimate the mass-loss rate of the stellar wind that drives the molecular outflow in the VLM objects, we can assume that the stellar wind-molecular gas interaction is momentum-conserving (e.g., Levreault 1988b; André et al. 1990). We thus equate the momentum P = Mout v_max of the molecular outflow with that supplied by the wind over the outflow’s lifetime (Mwind tdyn). This yields the expression \( M_{\text{wind}} = M_{\text{out}} \frac{v_{\text{max}}}{t_{\text{dyn}} v_{\text{wind}}} \), where \( v_{\text{wind}} \) is the wind velocity. For ISO-Oph 102, the wind velocity is \( \sim 107 \) km s⁻¹, which is estimated from \( v_{\text{Gaia}} = 45 \) km s⁻¹ (Whelan et al. 2005) with a correction of outflow inclination of \( \sim 65° \) to the line of sight (Phan-Bao et al. 2008). For the cases of MHO 5 and GM Tau, as no measurements of wind velocities have been reported so far, we assume a wind velocity of about 100 km s⁻¹ for these two objects. Using the upper and lower limits of outflow mass (see Table 2), we derive the upper and lower limits (Table 3) to the wind mass-loss rates of the VLM objects, respectively.

There is a possibility that our values of wind mass-loss rates are underestimated if the momentum from the wind might not be transferred all to the molecular gas. This happens when there is less molecular gas surrounding the source at late stages (class II) than early stages (class 0, I). However, the wind mass-loss rates of VLM objects (e.g., ISO-Oph 102) estimated from molecular outflows (see Table 2) are comparable to those derived from optical jets using the spectro-astrometric method (see Table 6 in Whelan et al. 2009, Whelan et al. 2014). This implies that our values are not significantly underestimated. All these values of wind mass-loss rates of VLM objects are smaller than a typical value of \( \sim 10^{-7} M_\odot \) yr⁻¹ for class-II low-mass stars of 0.5–5.0 M⊙ (Levreault 1988a) by over an order of magnitude (see Figure 3). Our results have shown that the outflow process occurring in VLM objects is a scaled-down version of that in low-mass stars.

We should note here that the ratios of wind mass-loss rate to mass accretion rate \( v_{\text{wind}}/M_{\text{acc}} \) in ISO-Oph 102 and MHO 5 (see Table 3) are significantly higher than that in T Tauri stars \( \sim 0.0003–0.4; \) Hartigan et al. 1995). These high ratio values imply three possible scenarios.

1. First, we might underestimate the accretion rates as the accretion rates measured in the VLM objects at different epochs may vary over an order of magnitude on timescales.
of months to years (e.g., Stelzer et al. 2007). Therefore, the rates measured at particular epochs do not reflect the long-term accretion rates that are more appropriate for comparison with the outflow rates in the two VLM objects. However, the accretion rate in MHO 5 measured at different epochs has suggested that the accretion rate is stable, $\sim 10^{-9.8} M_\odot \, yr^{-1}$ (Muzerolle et al. 2003; Herczeg & Hillenbrand 2008). In the case of ISO-Oph 102, the accretion rate of $\sim 10^{-9.0} M_\odot \, yr^{-1}$ was measured at epoch 2003.411 (Natta et al. 2004), and an increase of the accretion rate by a factor of five within a week was also observed (Natta et al. 2004). However, the accretion rate of $10^{-9.17} M_\odot \, yr^{-1}$ (Gatti et al. 2006) measured at epoch 2005.384 agrees with Natta et al.’s measurement, suggesting a longer-term accretion rate in ISO-Oph 012 of $\sim 10^{-9.0} M_\odot \, yr^{-1}$. Therefore, this scenario is unlikely the case here.

2. Second, we might overestimate the wind mass-loss rate. This is due to the fact that we did not apply a correction factor for the dynamical time (see Table 3). If the estimated dynamical time is a lower limit to the real dynamical time, then we need to apply a correction factor of about 100 for the case of ISO-Oph 102 and MHO 5 as well as GM Tau (see Section 5.2 for further discussion), instead of 10 as estimated for low-mass stars (Parker et al. 1991) for the outflow dynamical time of VLM objects. The wind mass-loss rates, and hence the ratios $\dot{M}_{\text{wind}}/\dot{M}_{\text{acc}}$, will decrease by the same factors and they are thus comparable to those in T Tauri stars.

3. Third, this ratio in VLM objects is really higher than that in low-mass stars. This is possibly due to a sudden drop of the mass accretion rate during the formation process of brown dwarfs as proposed by Machida et al. (2009). Further observations and theoretical works are needed to confirm these possible scenarios.

5.2. Episodic Outflows?

The outflow dynamical times estimated for the three class-II VLM objects, ISO-Oph 102 (Phan-Bao et al. 2008), MHO 5 (Phan-Bao et al. 2011), and GM Tau (this paper) are from $7.0 \times 10^2 \, yr$ to $2.7 \times 10^3 \, yr$ (see Table 2). These values are still about two or three orders of magnitude smaller than the ages of ISO-Oph 102, GM Tau, and MHO 5 expected to be from a few $10^5 \, yr$ (ISO-Oph 102; Natta et al. 2004) to a few Myr (GM Tau and MHO 5, see Muzerolle et al. 2003 and references therein).

The extreme discrepancy between the outflow dynamical time and the age of the VLM objects indicates two possibilities.

1. The extent of outflows is not completely revealed because of the coverage and the sensitivity of our observations. For example, an outflow with velocity of 5 km s$^{-1}$ and a dynamical time of $10^5 \, yr$ will have a length of about 0.5 pc, or 12’ at the distance of Taurus. This is more than an order of magnitude larger than the SMA primary beam size. Therefore, any molecular outflow emission that lies more than half a primary beam from the source would be impossible to detect. In addition, the full extent of outflows to the edge of the primary beam has not been detected (e.g., ISO-Oph 102; see Figure 1 in Phan-Bao et al. 2008), which is possibly due to the sensitivity limit of SMA. The estimated outflow dynamical time is thus a lower limit to the true outflow duration as discussed in Parker et al. (1991) for the case of low-mass stars.

2. The outflow process in the VLM objects is episodic, occurring in class II with duration of a few $10^3 \, yr$. An episodic outflow will have a discrete blob morphology. In this case, other blobs of the molecular outflows from our VLM objects that lie outside the primary beam would not be detected. The outflows detected by SMA are thus from the last active episodes. If the episodicity of these outflows is confirmed, the outflow process in VLM objects will include quiescent and active episodes. One can then expect that the accretion associated with the outflow is also episodic. This is consistent with evolutionary models as proposed by Baraffe et al. (2009) that the accretion process in BDs at early stages could be episodic, including long quiescent phases of accretion interrupted by short episodes (a few $10^3$ to $10^4 \, yr$) of high accretion. Their evolutionary models taking into account episodic phases
of accretion successfully explain the significant luminosity spread observed in H-R diagrams of star-forming regions.

More extended and deeper observations are therefore needed to explore the morphology of the outflows from these VLM objects in order to confirm the scenarios.

5.3. Molecular Outflows and the Formation of VLM Objects

The outflow masses and the mass-loss rates of the molecular outflows from ISO-Oph 102, GM Tau, and MHO 5, which are class II objects, are comparable to those of L1014-IRS (Bourke et al. 2005), a proto BD candidate at a younger age (class 0/I) that has an outflow with a mass and mass-loss rate of $\sim 10^{-5} M_\odot$ and $\sim 10^{-9} M_\odot$ yr$^{-1}$, respectively. In the case of the class I proto BD candidate L1148-IRS (Kauffmann et al. 2011), the outflow mass ($\sim 10^{-3} M_\odot$) and the mass-loss rate ($\sim 10^{-7} M_\odot$ yr$^{-1}$) are slightly larger than that from our VLM objects but still comparable to the range of our lower and upper limits (see Table 2). This similarity implies that the mass-loss rate, hence the associated wind mass-loss and accretion rates in VLM objects do not significantly change in different formation stages (from class 0/I to class II).

As discussed in Section 5.1, the ratio of wind mass-loss rate to accretion rate $M_{\text{wind}}/M_{\text{acc}}$ in VLM objects is possibly higher than that in low-mass stars (Table 3). If the wind mass-loss rate does not significantly change for different classes of VLM object formation, $10^{-11}-10^{-8} M_\odot$ yr$^{-1}$ (see Table 3), then one may expect that this ratio also holds in earlier classes, such as classes 0, I. This suggests that the accretion rate in VLM objects may also be expected to be in the range $10^{-11}-10^{-9} M_\odot$ yr$^{-1}$ at earlier stages. The starlike models for BD formation predict that VLM cores produced by fragmentation (Padoan & Nordlund 2004; Bonnell et al. 2008) are dense enough to be gravitationally unstable. The detection of such a VLM core (André et al. 2012) supports these models. Our observations suggest that these VLM cores may undergo some active episodes of outflow and associated accretion with duration of a few $10^3$ yr. The accretion rates, however, are very low, in the range $10^{-11}-10^{-9} M_\odot$ yr$^{-1}$ or lower, and they are comparable or smaller than the mass-loss rate. This may therefore prevent the VLM cores from accreting enough material to become a star.

6. SUMMARY

Here, we report our latest search for molecular outflows from VLM objects. So far, we have detected molecular outflows from two BDs (one in ρ Ophiuchi and one in Taurus) and one VLM star in Taurus. Our results suggest that (1) the bipolar molecular outflow process in VLM objects is a scaled-down version of that in low-mass stars; (2) the outflow mass-loss and the associated mass accretion processes in VLM objects are possibly episodic with duration of a few thousand years; (3) the outflow mass-loss rate and the mass accretion rate during active episodes are very low and they do not significantly change for different stages of the formation process of VLM objects; and (4) a very low-mass accretion rate, possibly together with a high ratio of outflow mass-loss rate to mass accretion rate, may prevent a VLM core from accreting enough gas to become a star; thus, the core will end up as a BD.