Publications of the Korean Astronomical Society
30: 083 ∼ 086, 2015 September

pISSN: 1225-1534
eISSN: 2287-6936
http://dx.doi.org/10.5303/PKAS.2015.30.2.083

MOLECULAR OUTFLOWS AND THE FORMATION PROCESS OF VERY LOW-MASS OBJECTS

Ngoc Phan-Bao[1,2], Cuong Dang-Duc[1,4], Chin-Fei Lee[2], and Paul T. P. Ho[2,3]

[1]Department of Physics, International University-Vietnam National University HCM, Block 6, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
[2]Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan, Republic of China
[3]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[4]Faculty of Physics and Engineering Physics, University of Science-Vietnam National University HCM, 227 Nguyen Van Cu Street, District 5, Ho Chi Minh City, Vietnam

E-mail: pbngoc@hcmiu.edu.vn

(Received November 30, 2014; Reviced May 31, 2015; Aaccepted June 30, 2015)

ABSTRACT

We present observational results characterizing molecular outflows from very low-mass objects in ρ Ophiuchi and Taurus. Our results provide us with important implications that clarify the formation process of very low-mass objects.

Key words: ISM: jets and outflows — ISM: individual (ISO-Oph 102, GM Tau, MHO 5) — stars: formation — stars: low mass, brown dwarfs — technique: interferometric

1. INTRODUCTION

In the early sixties, the existence of brown dwarfs (13–75 M_J) was predicted by Kumar (1963), but the first brown dwarfs were not observationally confirmed until 1995 (Rebolo et al., 1995; Nakajima et al., 1995). To date, thousands of very low-mass (VLM) stars (0.1–0.2 $M_\odot$) and brown dwarfs (BDs) have been discovered in star-forming regions and in the field, including BDs with temperatures as cool as the human body.

Since VLM stars and BDs (hereafter VLM objects) have masses much lower than the classical Jeans mass ($\sim$1 $M_\odot$), it is therefore difficult to produce a VLM object by direct gravitational collapse of molecular clouds. Several mechanisms have therefore been proposed for the formation of VLM objects (see Whitworth et al. 2007 and references therein). While all these mechanisms are possible and may occur in specific cases, observations of the statistical properties, e.g., initial mass function, velocity dispersion, multiplicity, accretion, and jets (see Luhman et al. 2007 and references therein) of VLM objects have shown that the properties of VLM objects form a continuum with those of low-mass stars. This strongly supports the scenario that VLM objects and low-mass stars form in the same manner and thus supports the starlike models (Padoan & Nordlund, 2004; Bonnell et al., 2008). In these models, dense cores of any size in the mass range of VLM objects and low-mass stars are produced directly by the processes of turbulent fragmentation (Padoan & Nordlund, 2004) or gravitational fragmentation (Bonnell et al., 2008). These processes produce high-density gas (i.e., low Jeans masses) and thus form VLM cores. These VLM cores are dense enough to be gravitational unstable and collapse. Recent detections of proto BD candidates (e.g., André et al. 2012; Palau et al. 2014) support these models. However, it is still unclear how the physical processes of VLM object formation occur at later stages (e.g., class 0, I, and II).

Because bipolar molecular outflows are a basic component of the physical process of star formation, we have therefore studied molecular outflow properties of VLM objects to understand their formation mechanism. In this paper, we present basic properties of molecular outflows observed in VLM objects in ρ Ophiuchi and Taurus. We then discuss these properties in the context of the formation mechanism of VLM objects.

2. THE OUTFLOW PROCESS IN VLM OBJECTS

We have observed eight targets in ρ Ophiuchi and Taurus (Phan-Bao et al., 2008, 2011, 2014) with the Submillimeter Array (SMA)[1] and the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at 230 GHz frequency to search for ^{12}CO $J = 2 \rightarrow 1$ outflows. These targets are Class II VLM objects. This indicates that the sources are reaching their final mass and thus they will end up as VLM objects. We have detected ^{12}CO $J = 2 \rightarrow 1$ outflows from three of the eight targets: ISO-Oph 102 (60 M_J, Phan-Bao et al. 2008) in ρ Ophiuchi, MHO 5 (90 M_J, Phan-Bao et al. 2011), and GM Tau (73 M_J, Phan-Bao et al. 2014) in

[1]The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

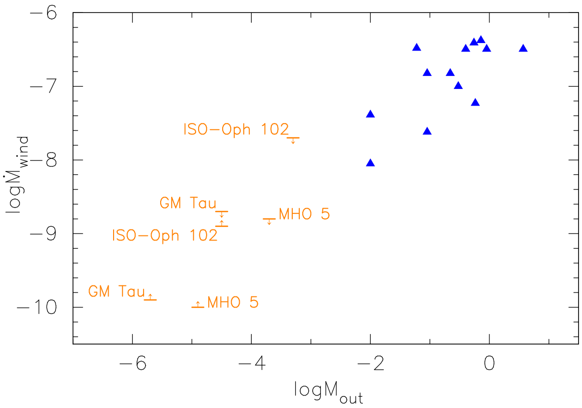

Figure 1. Comparison between the molecular outflow mass and the wind mass-loss rate of the three VLM objects (ISO-Oph 102, GM Tau, and MHO 5) and class II low-mass stars (blue triangles) with masses from 0.5 to 5.0 $M_\odot$ (Levreault, 1988a). The up and down arrows indicate the lower and upper limits, respectively.

Taurus. The CO outflow properties of the three VLM objects are listed in Table 1.

2.1. *Basic Properties*

The molecular outflows from the VLM objects show similar properties: a small scale of 600-1000 AU, a low velocity of <5 km s^{-1}, a very low outflow mass of 10^{-6}–10^{-4} $M_\odot$, and a low mass-loss rate of 10^{-9}–10^{-7} $M_\odot$ yr^{-1}.

We then estimate the mass-loss rate $\dot{M}_{\rm wind}$ of the stellar wind, which drives the molecular outflow in the VLM objects. We assume that momentum is conserved for the stellar wind-molecular gas interaction and thus equate the momentum of the molecular outflow, $P = M_{\rm out} v_{\rm max}$, with that supplied by the stellar wind during the outflow's lifetime, $\dot{M}_{\rm wind} t_{\rm dyn} v_{\rm wind}$ (e.g., Levreault 1988b). The wind velocity for ISO-Oph 102 is taken to be 107 km s^{-1}, which is estimated from a jet velocity of 45 km s^{-1} (Whelan et al., 2005) with a correction for an outflow inclination of $\sim 65°$ to the line of sight (Phan-Bao et al., 2008). For GM Tau and MHO 5, a wind velocity of 100 km s^{-1} is assumed because the wind velocities of these two objects have not been measured so far. Table 2 lists the upper and lower limits of the wind mass-loss rates of the three VLM objects that are derived from the upper and lower limits of the molecular outflow mass, respectively.

Our observational results have shown that the molecular outflow masses in the three VLM objects are over an order of magnitude smaller than the typical values of 0.01−0.7 $M_\odot$ for class II low-mass stars (Levreault, 1988b). The wind mass-loss rates of 10^{-10}–10^{-8} $M_\odot$ yr^{-1} are also over an order of magnitude smaller than the typical value of $\sim 10^{-7} M_\odot$ yr^{-1} (Levreault, 1988a) as shown in Figure 1. This therefore demonstrates that the outflow process in VLM objects occurs as a scaled-down version of that in low-mass stars.

2.2. *Episodicity*

Our estimated dynamical times for the outflow process in the three VLM objects (see Table 1) are in the range of 700 yr to 2700 yr. These values are smaller than the ages of these objects, expected to be from a few 10^5 yr for ISO-Oph 102 (Natta et al., 2004) to a few Myr for GM Tau and MHO 5 (see Muzerolle et al. 2003 and references therein), by two or three orders of magnitude.

The extreme discrepancy between the dynamical times of the outflows and the ages of the VLM objects indicates two possible scenarios.

1. The extent of molecular outflows in the VLM objects is not fully detected because of the sensitivity and the coverage of our observations. The estimated dynamical times of the outflows are thus lower limits to the real dynamical times (Parker et al., 1991). We then need to apply a correction factor of about 100 for the case of ISO-Oph 102 and 1000 for MHO 5 and GM Tau to determine the real dynamical times of the outflows. The molecular outflow mass-loss rates $\dot{M}_{\rm mol}$ (Table 1), the wind mass-loss rates $\dot{M}_{\rm wind}$ and the ratios $\dot{M}_{\rm wind}/\dot{M}_{\rm acc}$ (Table 2) will thus decrease by the same factors.
2. The outflow process in the VLM objects is episodic with a duration of a few thousand years. If this episodicity of the outflows is confirmed, the outflow process and thus the associated accretion process in VLM objects will include quiescent and active episodes. The episodicity of the accretion process in our VLM objects is consistent, in general, with evolutionary models as proposed for low-mass stars and BDs (see Baraffe et al. 2009 and reference therein). In the models, the accretion process in BDs at early stages may be episodic with long quiescent phases of accretion interrupted by short episodes of high accretion.

Further observations are needed to confirm these scenarios.

3. MOLECULAR OUTFLOWS AND THE FORMATION PROCESS OF VLM OBJECTS

There are two important points that we should discuss here.

First, the estimated ratios of wind mass-loss rate to mass accretion rate in our VLM objects (Table 2) are significantly higher than the values of $\sim$0.0003−0.4 (Hartigan et al., 1995) for T Tauri stars. There are two possible explanations.

1. We might overestimate the wind mass-loss rate because we did not apply a correction factor for the dynamical time of the outflow process (see Section 2.2). If a correction factor is applied, these ratios will decrease by the same factor and they are thus comparable to those in T Tauri stars.
2. This ratio in VLM objects is really higher than that in low-mass stars.

As discussed in Section 2.2, more observations are needed to confirm the episodicity of the outflow process

Table 1
BASIC PROPERTIES OF MOLECULAR OUTFLOWS OF THREE CLASS II VLM OBJECTS IN ρ OPHIUCHI AND TAURUS

Target	Mass (M_J)	size (length) (AU)	v_{max} (km s^{-1})	logM_{out}^{a} ($M_\odot$)	log$\dot{M}_{mol}$^{a} ($M_\odot$ yr^{-1})	logM_{out}^{b} ($M_\odot$)	log$\dot{M}_{mol}$^{b} ($M_\odot$ yr^{-1})	t_{dyn} (yr)	Reference
ISO-Oph 102	60	1000	4.7	−4.5	−7.5	−3.3	−6.3	1100	1, 2
GM Tau	73	700	4.6	−5.7	−8.6	−4.5	−7.4	700	3, 4
MHO 5	90	600	2.1	−4.9	−8.3	−3.7	−7.1	2700	5, 6

REFERENCES: —References for mass estimate of the VLM objects, molecular outflow mass and mass-loss rate: (1) Natta et al. (2004); (2) Phan-Bao et al. (2008); (3) White & Basri (2003); (4) Phan-Bao et al. (2014); (5) Muzerolle et al. (2003); (6) Phan-Bao et al. (2011).
NOTE: —[a]Lower limits of molecular outflow mass and mass-loss rate without mass corrections.
[b]Upper limits of molecular outflow mass and mass-loss rate with mass corrections: a factor of three for SMA missing flux (Bourke et al., 2005) and five for optical depth (Levreault, 1988a).

Table 2
WIND MASS-LOSS RATE OF THREE VLM OBJECTS WITH DETECTED MOLECULAR OUTFLOWS

Target	log$\dot{M}_{acc}$ ($M_\odot$ yr^{-1})	log$\dot{M}_{wind}$^{a} ($M_\odot$ yr^{-1})	log$\dot{M}_{wind}$^{b} ($M_\odot$ yr^{-1})	$\dot{M}_{wind}/\dot{M}_{acc}$^{c}	Reference
ISO-Oph 102	−9.0	−8.9	−7.7	1.3-20.0	1
GM Tau	−8.6	−9.9	−8.7	0.05-0.8	2
MHO 5	−10.8	−10.0	−8.8	6.3-100.0	3

REFERENCES: —References for accretion rate: (1) Natta et al. (2004); (2) White & Basri (2003); (3) Muzerolle et al. (2003).
NOTE: —[a]Lower limit of wind mass-loss rate.
[b]Upper limit of wind mass-loss rate.
[c]The range of the ratio of wind mass-loss rate to the accretion rate.

in VLM objects and hence clarify these two possibilities.

Second, the basic properties of the outflow process in our VLM objects such as masses, and mass-loss rates are comparable to those observed in proto BD candidates at earlier stages, e.g., L1014-IRS (class I, Bourke et al. 2005) or IC 348-SMM2E (class 0, Palau et al. 2014). The similarity implies that the mass-loss rate, and hence the associated accretion rate in VLM objects does not change considerably at different stages of the VLM object formation. This therefore suggests a very low accretion rate in the range 10^{-11}–10^{-9} $M_\odot$ yr^{-1} (Table 2) for different stages of the formation process of VLM objects.

4. SUMMARY

Our results show that (i) the bipolar molecular outflow process in very low-mass objects is a scaled-down version of that in low-mass stars; (ii) the outflow and the associated accretion processes are possibly episodic with a duration of a few thousand years; (iii) the accretion rate is very low and it does not significantly change for different stages of VLM object formation. We therefore suggest a possible scenario for the formation mechanism of VLM objects, that the episodic accretion process with a very low accretion rate, possibly together with a high ratio of outflow mass-loss rate to mass accretion rate, may prevent a very low-mass core from accreting enough gas to become a star and thus the core will end up a very low-mass object.

ACKNOWLEDGMENTS

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.08-2013.21. Support for CARMA construction was derived from the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the James S. McDonnell Foundation, the Associates of the California Institute of Technology, the University of Chicago, the states of California, Illinois, and Maryland, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

REFERENCES

André, P., Ward-Thompson, D., & Greaves, J., 2012, Interferometric Identification of a Pre-Brown Dwarf, Science, 337, 69
Baraffe, I., Chabrier, G., & Gallardo, J., 2009, Episodic Accretion at Early Stages of Evolution of Low-Mass Stars and Brown Dwarfs: A Solution for the Observed Luminosity Spread in H-R Diagrams?, ApJ, 702, L27
Bonnell, I. A., Clark, P., & Bate, M. R., 2008, Gravitational Fragmentation and the Formation of Brown Dwarfs in Stellar Clusters, MNRAS, 389, 1556
Bourke, T. L., Crapsi, A., & Myers, P. C., et al., 2005, Discovery of a Low-Mass Bipolar Molecular Outflow from L1014-IRS with the Submillimeter Array, ApJ, 633, L129
Hartigan, P., Edwards, S., & Ghandour, L., 1995, Disk Accretion and Mass Loss from Young Stars, ApJ, 452, 736
Kumar, S. S., 1963, The Structure of Stars of Very Low Mass, ApJ, 137, 1121
Levreault, R. M., 1988a, A search for Molecular Outflows toward the re-main-sequence Objects, ApJS, 67, 283
Levreault, R. M., 1988b, Molecular Outflows and Mass Loss in the pre-main-sequence Stars, ApJ, 330, 897
Luhman, K. L., Joergens, V., Lada, C., Muzerolle, J., Pas-

cucci, I., & White, R., 2007, The Formation of Brown Dwarfs: Observations, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 443

Muzerolle, J., Hillenbrand, L., Calvet, N., Briceño, C., & Hartmann, L., 2003, Accretion in Young Stellar/Substellar Objects, ApJ, 592, 266

Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T., 1995, Discovery of a Cool Brown Dwarf, Nature, 378, 463

Natta, A., Testi, L., Muzerolle, J., Randich, S., Comerón, F., & Persi, P., 2004, Accretion in Brown Dwarfs: An Infrared View, A&A, 424, 603

Padoan, P., & Nordlund, Å. 2004, The "Mysterious" Origin of Brown Dwarfs, ApJ, 617, 559

Palau, A., et al., 2014, IC 348-SMM2E: A Class 0 Proto-Brown Dwarf Candidate Forming as a Scaled-Down Version of Low-Mass Stars, MNRAS, 444, 833

Parker, N. D., Padman, R., & Scott, P. F., 1991, Outflows in Dark Clouds - Their Role in Protostellar Evolution, MNRAS, 252, 442

Phan-Bao, N., et al., 2008, First Confirmed Detection of a Bipolar Molecular Outflow from a Young Brown Dwarf, ApJ, 689, L141

Phan-Bao, N., Lee, C.-F., Ho, P. T. P., & Tang, Y.-W., 2011, Molecular Outflows in the Substellar Domain: Millimeter Observations of Young Very Low Mass Objects in Taurus and rho Ophiuchi, ApJ, 735, 14

Phan-Bao, N., Lee, C.-F., Ho, P. T. P., Dang-Duc, C., & Li, D., 2014, Characterization of Molecular Outflows in the Substellar Domain, ApJ, 795, 70

Rebolo, R., Zapatero Osorio, M. R., & Martín, E. L., 1995, Discovery of a brown dwarf in the Pleiades star cluster, Nature, 377, 129

Whelan, E. T., Ray, T. P., Bacciotti, F., Natta, A., Testi, L., & Randich, S., 2005, A Resolved Outflow of Matter from a Brown Dwarf, Nature, 435, 652

White, R. J., & Basri, G., 2003, Very Low Mass Stars and Brown Dwarfs in Taurus-Auriga, ApJ, 582, 1109

Whitworth, A., Bate, M. R., Nordlund, Å., Reipurth, B., & Zinnecker, H., 2007, The Formation of Brown Dwarfs: Theory, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 459