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A PROTO-BROWN DWARF CANDIDATE IN ρ OPHIUCHUS

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Abstract. *Brown dwarfs with masses below 0.075 solar masses are thought to form like low-mass stars (e.g., the Sun). However, it is still unclear how the physical formation processes occur in brown dwarfs at the ealiest stages (i.e., proto-brown dwarfs) of their formation. Up to date, only a few proto-brown dwarfs have been detected. The detection of proto-brown dwarfs offers us excellent benchmarks to study the formation process of brown dwarfs, and thus understand their formation mechanism. In this paper, we present our identification of a proto-brown dwarf candidate in the star-forming region ρ Ophiuchus. The candidate shows a small-scale bipolar molecular outflow that is similar to the outflows observed in other young brown dwarfs. The detection of this candidate provides us with additional important implications for the formation mechanism of brown dwarfs.*

Keywords: brown dwarfs, formation of stars, interferometry, protostars.

Classification numbers: 97.20.Vs; 97.10.Bt; 95.55.Br; 97.21.+a.

I. INTRODUCTION

Brown dwarfs (BDs) have masses from 0.013 to 0.075 $M_{\odot}$, and they are very popular in our Galaxy. Based on the WISE data [1], astronomers have estimated that 6 stars exist for every BD in the Galaxy. As the BD mass is below the hydrogen-burning limit ($\sim$0.075 $M_{\odot}$), the physical properties of BDs as well as their formation mechanism have intensively been debated in the last decades.

Regarding the formation mechanism of BDs, on the theoretical side it has been proposed that BDs form by turbulent [2] or gravitational [3] fragmentation of molecular clouds or ejection of BD embryos [4]. In the fragmentation models, BD cores that are produced by the processes of turbulent or gravitational fragmentation are dense enough to collapse under gravity. In the ejection model, BD embryos are ejected off from their gas reservoir and thus they can not accrete more materials to become stars.

On the observational side, statistical results have strongly indicated that BDs share similar properties with low-mass stars, such as outflows, accretion, initial mass function, binarity and kinematics (see a review in [5]). This implies that BDs form in the same manner as low-mass stars. Thus, the issue has been raised that BDs may exist in all evolutionary stages of formation as low-mass stars do, from BD cores to class 0 and I BDs, i.e., proto-BDs (e.g., see Phan-Bao Ngoc's talk in the meeting "The origin of stellar masses" organized at Tenerife in 2010 [1]). Therefore, it is important to detect these proto-BDs in star-forming regions, and then to study how the formation processes take place in these detected proto-BDs. This will allow us to fully understand how BDs form physically, not statistically. So far, only a few candidates of proto-BDs have been identified. In 2012, a BD core whose the estimated final mass is substellar was discovered [6] in the Ophiuchus cloud. In 2014, a class 0 BD in Perseus was detected [7]. In 2016, we identified 2 class I BDs, [GKH94] 41 and IRAS 04191+1523B in Taurus [8]. Recently, two additional class 0 BDs have been reported [9, 10].

In this paper, we report our identification of a class 0/I proto-BD candidate in ρ Ophiuchus based on the Submillimeter Array (SMA) observations. Section 2 presents our millimeter observations and the data reduction. We determine the properties of molecular outflows from the candidate in Section 3 and summarize the results in Section 4.

II. OBSERVATIONS AND DATA REDUCTION

The proto-BD was serendipitously identified in ρ Ophiuchus during the observations of the class II BD, ISO-Oph 102. The discovery of a bipolar molecular outflows from ISO-Oph 102 was published in [11]. The proto-BD had been observed on June 3, 2008 with the SMA receiver band at 230 GHz. Both 2 GHz-wide sidebands were used. We used the SMA correlator with a high spectral resolution of 0.27 km s^{-1} (or 0.203 MHz) for ^{12}CO, ^{13}CO, and C^{18}O $J = 2 \rightarrow 1$ lines. The remainder of each sideband was set up with a lower resolution of 4.3 km s^{-1} (or 3.25 MHz). The quasars 3C 279 and 1625$-$254 had been observed for passband and gain calibration, respectively. We used Mars for flux calibration. We then used the MIR software to reduce data and the MIRIAD package to analyze data. We also applied the primary beam correction to the data. The compact configuration of SMA was used, resulting in a synthesized beam of $3''.60 \times 2''.43$ with a position angle of 8.5°. The rms sensitivity was $\sim$2 mJy for the continuum and $\sim$0.24 Jy beam^{-1} per channel for the spectral line data.

We identified the proto-BD at a separation of $\sim 20''$ from ISO-Oph 102. The coordinates of the proto-BD are $\alpha_{\rm J2000} = 16^{\rm h}27^{\rm m}05.03^{\rm s}$, and $\delta_{\rm J2000} = -24°41'50.6''$. The flux density of the dust continuum emission measured at the proto-BD (hereafter SMA1627$-$2441) is 7$\pm$2 mJy. Thus, the continuum is marginally detected at only 3.5 σ.

III. BIPOLAR OUTFLOW FROM SMA1627$-$2441 AND ITS PROTO-BD NATURE

III.1. Bipolar outflow from SMA1627$-$2441

Our map of carbon monoxide (CO $J = 2-1$) line emission is shown in Fig. 1. The blue- and red-shifted components are separated into two distinct lobes by the position-velocity (PV) diagram (Fig. 2). The blue-shifted and red-shifted components are in the ranges of 3.8$-$4.8 km s^{-1} and 5.1$-$5.9 km s^{-1}, respectively. These two components are almost completely overlapped in the

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[1] http://research.iac.es/congreso/constellation10/media/talks/Phan-Bao_tenerife.pdf

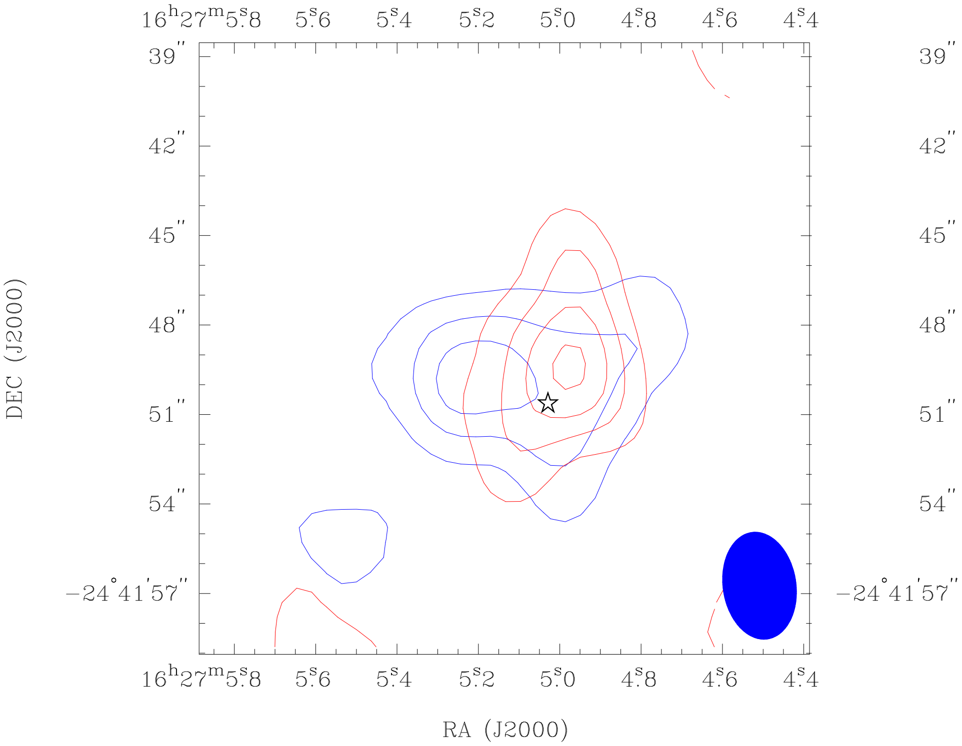

Fig. 1. Carbon monoxide (CO $J = 2-1$) emission map around SMA1627−2441. The intensity is integrated over the velocity range of from 3.8 to 5.9 km s^{-1}. The red and blue contours show the red-shifted (integrated from 5.1 and 5.9 km s^{-1}) and blue-shifted (integrated from 3.8 and 4.8 km s^{-1}) emissions, respectively. The contours are -3, 3, 6, 9,...times the rms of 0.24 Jy beam^{-1} km s^{-1}. The star symbol represents the position of SMA1627−2441. The position angle of the outflow is about 90°. The synthesized beam is shown in the bottom right corner.

CO map (Fig. 1). This suggests that the outflow direction is very close to the line of sight. The outflow inclination can be determined by the disk modeling (see [11]) that requires more data in optical and infrared. However, no optical and infrared observations of SMA1627−2441 have been reported so far. Therefore, we assume that the inclination angle of the disk of SMA1627−2441 is about 15° for the following calculation of outflow parameters. To calculate the outflow properties, we use the same manner as used in the previous papers [11–13].

First, we use the excitation temperature of 20 K, and we derive a lower limit value of outflow mass of $\sim 1.7 \times 10^{-5} M_{\odot}$. For the upper limit value, the correction factors due to optical depth and missing flux need to be taken into account. However, for the case of SMA1627−2441 these factors are unknown. Therefore, we assume an optical depth of five [14] and an SMA missing flux factor of three [15] to obtain an upper limit value of outflow mass of $\sim 2.7 \times 10^{-4} M_{\odot}$. The

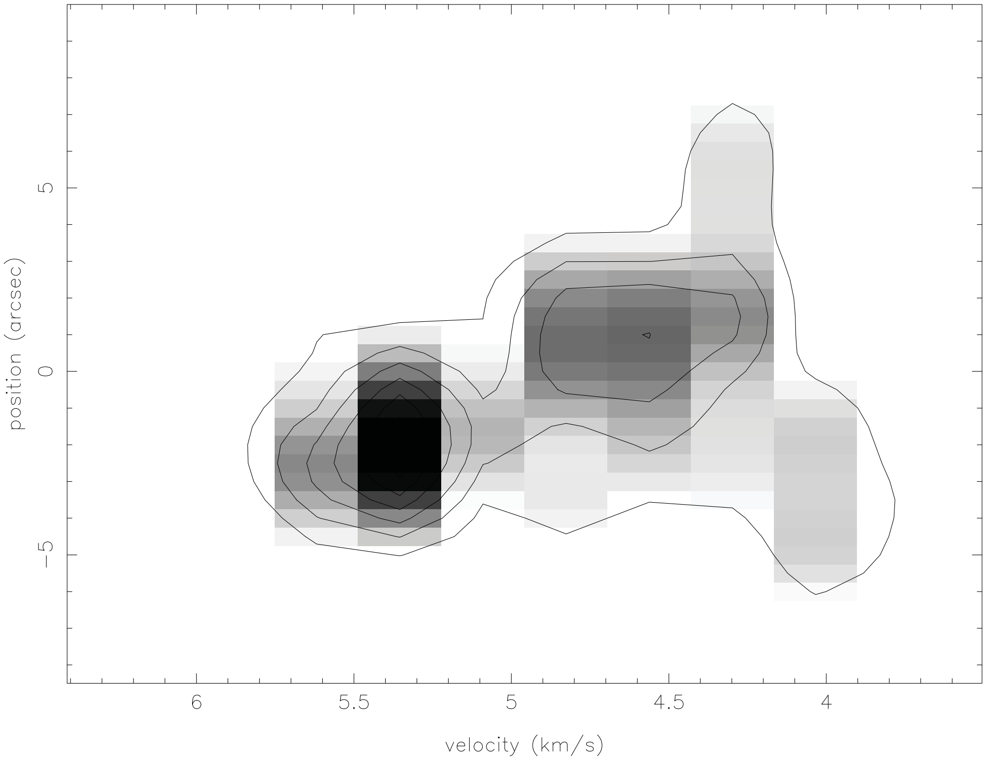

Fig. 2. Position-Velocity diagram for CO emission at a position angle of 90°. The contours are 3, 6, 9, 12,...times the rms of 0.3 Jy beam^{-1}. Both blue- and red-shifted components show compact and low-velocity outflows that are consistent with the properties of outflows observed in other proto-BDs.

PV diagram (Fig. 2) implies an observed maximum velocity of outflows of about 1.0 km s^{-1}. The correction of the outflow inclination of 15° results in a maximum outflow velocity of 1.04 km s^{-1}.

Using the lower limit value of outflow mass, we then derive the momentum $P = 1.8 \times 10^{-5} M_\odot$ km s^{-1} and the energy $E = 9.1 \times 10^{-6} M_\odot$ km^2 s^{-2}. The size of the blue- and red-shifted lobes is about 10$''$, corresponding to 1250 AU at a distance of 125 pc (distance to ρ Ophiuchus) of SMA1627−2441. After correcting the outflow inclination, we then derive a dynamical time for the proto-BD of about 22100 yr, the force $F = 7.9 \times 10^{-10} M_\odot$ km s^{-1} yr^{-1}, and the mechanical luminosity $L = 6.8 \times 10^{-8}$ L$_\odot$, where L$_\odot$ is the solar luminosity. If we use the upper limit value of outflow mass, the values of these kinematic and dynamic quantities will increase by a factor of fifteen. Using the dynamical time, the lower and upper limit values of outflow mass as computed above, we derive the lower and upper limits to the mass outflow rate in SMA1627−2441 to be $7.7 \times 10^{-10} M_\odot$ yr^{-1} and $1.2 \times 10^{-8} M_\odot$ yr^{-1}, respectively.

It is possible that the detected blue- and red-shifted emission might be due to gravitationally bound motion and not outflow emission. For the case of gravitationally bound motion, a size of $l = 1250$ AU with a velocity of about $v = 1.0$ km s^{-1} would require an enclosed mass of $\geq 0.8\ M_\odot$

($M \geq v^2 l/2G$, see [16]), which is significant larger than core masses of <0.4 $M_\odot$ with the same size in ρ Ophiuchus [17]. Therefore, we conclude that the detected emission is from the outflow.

III.2. Proto-BD nature of SMA1627−2441

First, the outflow mass in SMA1627−2441 is in the range from $1.7 \times 10^{-5} M_\odot$ to $2.7 \times 10^{-4} M_\odot$, which is smaller than the typical values of outflow mass of $0.01-0.07$ $M_\odot$ in low-mass stars [18] by two or three orders of magnitude. The outflow rate of $7.7 \times 10^{-10}-1.2 \times 10^{-8} M_\odot$ yr^{-1} in this proto-BD is also smaller than the typical value of outflow rate of $\sim 10^{-7} M_\odot$ yr^{-1} in low-mass stars [14] by about one or two orders of magnitude. This indicates that the outflow process occurs in BDs as a scaled-down version of that in low-mass stars.

Second, the outflow mass and the outflow rate in SMA1627−2441 are comparable to those observed in other proto-BDs, such as SMM2E (class 0) with an outflow mass of $3 \times 10^{-5} M_\odot$ and a mass outflow rate of $6 \times 10^{-8} M_\odot$ yr^{-1} [7], ISO-Oph 200 (class 0) with an outflow mass of $\sim 6 \times 10^{-5} M_\odot$ and a mass outflow rate of $\sim 10^{-8} M_\odot$ yr^{-1} [19]. This implies that SMA1627−2441 is a proto-BD.

The evolutionary stage of SMA1627−2441 can be determined based on its spectral energy distribution. Currently, we only have one SMA millimeter data point and the source has not been detected in any previous optical and infrared surveys. Therefore, we cannot determine the evolutionary stage of SMA1627−2441 with the current data. However, the dynamical time of the outflow of about 22100 yr suggests the proto-BD to be a class 0 or I source, which is similiar to the case of Mayrit 1701117 (class 0 or I, [10]) with an age of 30000−40000 yr. Using the continuum flux of 7±2 mJy at 1.33 mm, we also estimate the mass of the disk of the proto-BD. If we assume a dust emissivity $\beta = 1.4$ for class I objects [20], a dust opacity coefficient $\kappa_{870\mu\mathrm{m}} = 0.0175$ cm^2 g^{-1} [7], and a dust temperature of 20 K, we obtain an envelope mass of 2 M_J. The disk mass is very small and comparable to the previously estimated disk masses of class I proto-BDs (see [8]). This further supports that SMA1627−2441 is a proto-BD.

Finally, the outflow properties in SMA1627−2441 are also comparable to those in class II BDs [11–13]. This strongly suggests that the mass outflow rate, and hence the accretion rate, in different stages of BD formation remain very low. This may prevent BD cores, which are produced by the processes of turbulent or gravitational fragmentation, from accreting enough material to become stars as intensively discussed in [13].

IV. CONCLUSIONS

In this paper, we present our detection of a bipolar outflow from a class 0/I proto-BD. The outflow mass and the outflow rate in this proto-BD are smaller than the typical values in low-mass stars by over an order of magnitude. This strongly supports the scenario that BDs form in a scaled-down version of low-mass stars. The outflow properties in the class 0/I proto-BD SMA1627−2441 are also comparable to those in other class 0, I and II BDs. This further supports our scenario proposed for the BD formation [13] that the outflow rate and the associated accretion rate in proto-BDs are very low and they do not significantly change in different evolutionary stages of BD formation. This prevents very low mass cores from accreting more material and these cores will end up with BD masses. The current data suggests that SMA1627−2441 is a class 0 or I proto-BD. Further observations at different wavelengths are needed to confirm the nature of this proto-BD candidate.

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