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Research Article

IRAS 04325+2402ABC: A TRIPLE SYSTEM OF PROTOSTELLAR OBJECTS IS SPATIALLY RESOLVED BY THE SUBMILLIMETER ARRAY

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ABSTRACT

IRAS 04325+2402 is a protostellar system consisting of two objects AB and C. However, the double structure of object AB speculated as a binary system has still been a subject of debate. This paper presents the Submillimeter Array archival observations at millimeter wavelengths of this protostellar system. All three components A, B, and C are detected and spatially resolved, confirming the previously observed double structure as a binary system. In addition, the mass of the circumstellar reservoir (gas and dust) around these three components is also estimated.

Keywords: brown dwarfs; low-mass stars; star formation

1. Introduction

Protostellar objects are very young stellar objects that are still accreting material from their circumstellar reservoir (envelope and disk) during the formation phase. At the end of the formation phase, depending on the final mass, a protostellar object can become a star (mass above 75 M_J), brown dwarf (below 75 M_J), or even a planetary-mass object (below 13 M_J) (see Zapatero Osorio et al., 2000). Studying protostellar objects is essential because they provide us with clues to the understanding of their formation mechanism.

IRAS 04325+2402ABC is a protostellar system in the Taurus star-forming region. Based on near-infrared observations with the Hubble Space Telescope NICMOS Camera 2, Hartmann et al. (1999) found that the system consists of a central source IRAS 04325+2402AB and a protostar IRAS 04325+2402C, at a separation of about 8.2" from the central source. The central source may itself be binary as it shows a double structure, indicating two sources. IRAS 04325+2402AB is a class I system, and IRAS 04325+2402C is a class II object (Luhman et al., 2010). Based on the bolometric luminosity, Luhman et al.

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(2010) derived spectral types of K6–M3.5 for IRAS 04325+2402AB and M6–M8 for IRAS 04325+2402C. With the estimated ranges of spectral type, IRAS 04325+2402AB is a system of class I protostars, and IRAS 04325+2402C is a class II brown dwarf candidate. The system was then observed with the NIRI camera at the Gemini-North 8.1-m telescope by Scholz et al. (2010). Using the obtained near-infrared images, Scholz et al. (2010) found that the image of IRAS 04325+2402AB does not show any evidence for a second point source. Therefore, they concluded that the double structure observed in Hartmann et al. (1999) is possibly due to the presence of a disk seen at high inclination, not the presence of a second companion. Scholz et al. (2010) explained that the disk bisects the image of IRAS 04325+2402AB, resulting in a double structure.

In this paper, I present my study of the protostellar system IRAS 04325+2402ABC. I reduced and analyzed the observational data from the Submillimeter Array (SMA) archive. I then used the fluxes at millimeter wavelengths to estimate the mass of the circumstellar reservoir associated with each component of the system to determine the final masses of these objects. Section 2 presents the observations and data reduction. Section 3 presents the data analysis and discusses the final masses of components IRAS 04325+2402A, B, and C. Section 4 summarizes the results.

2. Observations and data reduction

IRAS 04325+2402ABC (component AB: $04^h35^m35.39^s+24^008'19.4''$, component C: $04^h35^m35.36^s+24^008'26.6''$) was observed on 2013 January 12 (Project: 2012B-A018) with SMA[1] (Ho et al., 2004) in the extended configuration. The receiver band at 230 GHz with both 2 GHz-wide sidebands, separated by 10 GHz, was used. The SMA correlator was configured with high spectral resolution bands of 512 channels per chunk of 104 MHz for ^{12}CO, ^{13}CO, and C^{18}O lines, corresponding a spectral resolution of 0.27 km s^{-1}. For the remainder of each sideband, a lower resolution of 32 channels per chunk was set up for the continuum detection. The zenith opacities at 225 GHz were excellent, below 0.2. The quasars 3C111, 3C120 were observed for gain and 3C279 for passband calibration. Callisto was used for flux calibration. The uncertainty in the flux calibration is about 20%.

I used the MIR software package to calibrate data and the MIRIAD package to analyze the calibrated data. The synthesized beam is 1.14"×0.85" for the natural weighting. The rms sensitivity is about 0.5 mJy for the continuum. The primary FWHM beam is about 48" at 230 GHz.

The continuum emission from IRAS 04325+2402ABC is clearly detected. The analysis of ^{12}CO molecular lines detected in IRAS 04325+2402 is not the scope of this paper,

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and it will be presented in a forthcoming paper.

3. Results and discussion

Figure 1 shows the continuum map at 217 GHz (or 1.38 mm) of IRAS 04325+2402ABC. Objects AB are spatially resolved into two components A and B. I therefore confirm that the double structure as observed in Hartmann et al. (1999) is a binary system consisting of component A and B. The separation between component A and B is about 1.7". The fluxes measured for each component are listed in Table 1.

The total flux of components A and B is 10.0±2.7 mJy, which agrees with the value of 10±3 mJy measured by Scholz et al. (2008) based on their observations at 1.3 mm with the IRAM Plateau de Bure Interferometer (IRAM PdBI). For the case of component C, our measured flux of 3.5±0.4 mJy is significantly lower than the value of 10±3 mJy measured by Scholz et al. (2008).

The continuum emission at 1.3 mm detected in the three components of the system IRAS 04325+2402 is originally from circumstellar gas and dust associated with each component. IRAS 04325+2402A and B are class I low-mass stars, the continuum emission is from both the envelope and the disk. However, for the case of component C, the source is a class II brown dwarf candidate, the continuum emission is therefore mainly from the disk as the envelope gas is expected to be almost dissipated at this stage.

The total mass of gas and dust M_{d} can be estimated from the flux S_λ at millimeter wavelength (1.38 mm) using the following formula for optically thin dust:

$$M_{\mathrm{d}} = \frac{S_\lambda d^2}{B(\lambda, T_{\mathrm{d}})\kappa_\lambda}$$

Where d is the distance to the source (d = 140 parsec for Taurus); T_{d} is the dust temperature; $\kappa_\lambda \propto \lambda^{-\beta}$ is the mass absorption coefficient of the dust at wavelength λ, and β is dust emissivity; $B(\lambda, T_{\mathrm{d}})$ is the Planck function, which depends on the wavelength and the dust temperature. The value of κ_λ at 1.38 mm is derived from $\kappa_{870\mu\mathrm{m}}$= 0.0175 cm^2g^{-1} and β = 1.4, a typical value for class I objects in Taurus (Chandler et al., 1998). A dust temperature of 20 K and a gas-to-dust ratio of 100 are assumed. The estimated masses for all three components are listed in Table 1. The dust mass is in the range of 1.7–2.5 M_J.

One should note that the value of β can be lower than 1 if grain growth up to millimeter sizes occurs in the components. In this case, the dust masses can be lower than the estimated values as listed in Table 1 by a factor of up to 2. More data at far-infrared wavelengths (see Dang-Duc et al., 2016) are needed to determine more precisely the value of β.

It is important to discuss the issue of missing flux in the interferometric observations. The total unresolved continuum flux for all three components IRAS 04325+2402ABC measured by the IRAM 30-m single dish is 110±7 mJy, which is significantly higher than the value of total resolved fluxes of 13.5±3.1 mJy for components A, B, and C measured by SMA. This indicates that the extended emission of a common envelope surrounding component A and B (see Figure 1) may be resolved out by SMA. The extended configuration of SMA offered a maximum recoverable scale of about 6.9" in comparison with a scale of 11" offered by the IRAM 30-m single dish. Thus, any extended emission at large-scales (>6.9") are almost completely resolved out by SMA. If I use the flux value of 110 mJy, the total dust mass of all three components will be about 54 M_J, which is higher than the total dust mass estimated from the SMA total flux by a factor of about 8. Therefore, one should expect that the actual dust mass of components IRAS 04325+2402A and B are higher than the values listed in Table 1 by a factor of 8. For component C, the actual dust mass may be only slightly higher the estimated value in Table 1 since the component is a class II object and the continuum emission is mainly from a small-scale disk.

Based on the bolometric luminosity, Luhman et al. (2010) estimated the spectral types of components IRAS 04325+2402AB and IRAS 04325+2402C to be K6–M3.5 and M6–M8, respectively. I thus consider an average combined spectral type of M1 for IRAS 04325+2402AB and M7 for IRAS 04325+2402C. Using theoretical models by Baraffe et al. (1998) and Chabrier et al. (2000) at an age of 1 Myr for the system, I then derived the current mass of the central object to be $0.85^{+0.35}_{-0.47}$ $M_{\odot}$ for IRAS 04325+2402AB and 57^{+40}_{-26} M_J for IRAS 04325+2402C. If I assume that components IRAS 04325+2402A and B have equal masses, with the average combined spectral type of M1, the spectral type of each component will be M3.5. In this case, the current mass of the central object of each component A and B

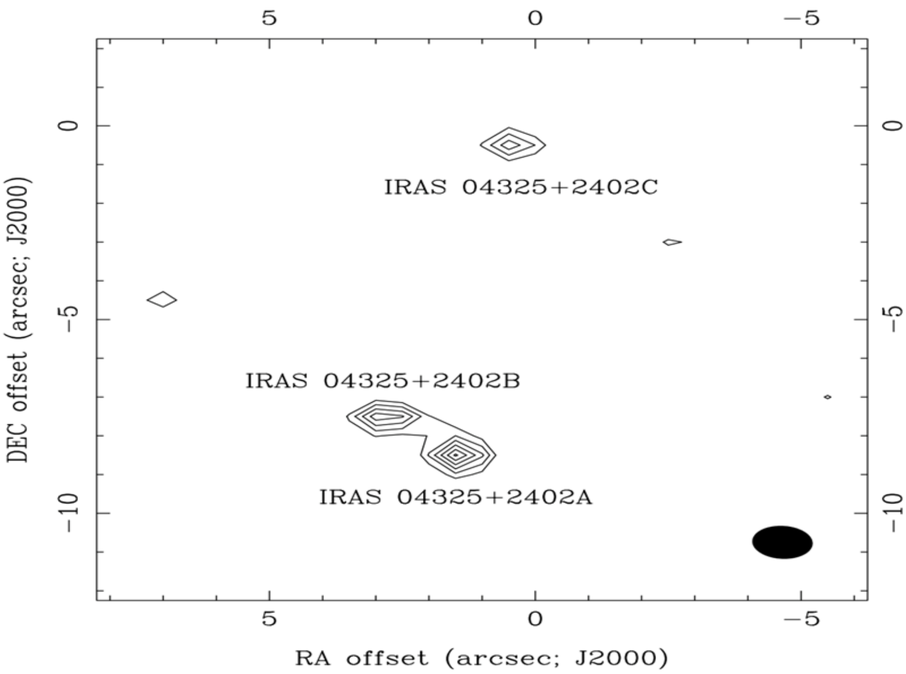

Figure 1. *Continuum emission map at 230 GHz of the triple system of protostellar objects IRAS 04325+2402ABC. The contours are 3,4,5,6,7, and 8 times the rms of 0.5 mJy beam^{-1}. The synthesized beam (1.14"×0.85") is shown in the bottom right corner. All three components A, B and C are spatially resolved*

Table 1. *Continuum fluxes measured at 1.38 mm for components IRAS 04325+2402A, B, and C*

Component	**Deconvolved major axis ('')**	**Deconvolved minor axis ('')**	**Position angle (^{0})**	**Flux (mJy)**	**Circumstellar mass (M_J)**
IRAS 04325+2402A	1.29±0.24[a]	1.04±0.18[a]	42±32	5.2±1.4	2.5±0.7
IRAS 04325+2402B	0.99±0.31	0.29±0.15	86±14	4.8±1.3	2.3±0.6
IRAS 04325+2402C	0.67±0.11	0.31±0.07	78±9	3.5±0.4	1.7±0.2

Notes: [a]*: Undeconvolved values;* M_J: *Jupiter mass*

is about 0.46 $M_\odot$.

The final mass of a protostellar object will be equal to the current mass of the central object plus the mass accreted from the associated circumstellar reservoir during the formation phase. Since the outflow process ejects a significant amount of material from the circumstellar reservoir, therefore, the current mass of the central object plus the mass of the associated disk and envelope is the upper limit to the final mass of the protostellar object. For IRAS 04325+2402AB, with the current mass of $0.85^{+0.35}_{-0.47}$ $M_\odot$ and the circumstellar mass of about 2–3 M_J, or 16–24 M_J if a factor of 8 due to the missing flux taken into account, IRAS 04325+2402A and B will become low-mass stars (above 0.35 $M_\odot$). For IRAS 04325+2402C, with the current mass of 57^{+40}_{-26} M_J and the circumstellar mass of 1.7 M_J, IRAS 04325+2402C will very likely become a brown dwarf (below 75 M_J).

4. Conclusion

This paper presents the SMA observations of the protostellar system IRAS 04325+2402ABC. The observations spatially resolve all three components of the system and thus confirm the presence of component B. The upper limits to the final mass of each component are also estimated. The estimated final masses suggest that IRAS 04325+2402A and B will become low-mass stars, and IRAS 04325+2402C will likely become a brown dwarf. This triple protostellar system consisting of two low-mass stars and one brown dwarf offers an excellent benchmark for studying the formation mechanism of low-mass stars and brown dwarfs.

❖ ***Conflict of Interest:*** *Author have no conflict of interest to declare.*

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**IRAS 04325+2402ABC: MỘT HỆ BA TIỀN SAO
ĐƯỢC PHÂN GIẢI KHÔNG GIAN VỚI HỆ KÍNH VÔ TUYẾN SMA**

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TÓM TẮT

IRAS 04325+2402 là một hệ tiền sao bao gồm một vật thể AB và một vật thể C. Tuy nhiên cấu trúc đôi của vật thể AB được cho là một hệ sao đôi đang là vấn đề tranh luận. Trong bài báo này, chúng tôi trình bày quan sát hệ IRAS 04325+2402 ở bước sóng milimét từ cơ sở dữ liệu của hệ kính vô tuyến SMA. Hình ảnh quan sát cho thấy cả ba thành phần A, B, và C đều được phát hiện rõ ràng và phân giải không gian. Kết quả quan sát này đã xác nhận cấu trúc đôi của vật thể AB quả thực là một hệ sao đôi. Ngoài ra, tôi còn ước tính khối lượng của khí và bụi bao quanh cả ba thành phần IRAS 04325+2402A, B, và C.

Từ khóa: sao có khối lượng rất thấp; sự hình thành sao; sao lùn nâu