**Extremely Dense Cores Associated with Chandra Sources in Ophiuchus A: Forming Brown Dwarfs Unveiled?**

Ryohei Kawabe1,2,3, Chihomi Hara4,5, Funmitaka Nakamura1,2,3, Kazuya Saigo1, Takeshi Kamazaki1, Yoshito Shimajiri6, Kengo Tomida7, Shigehisa Takakuwa3,9, Yohko Tsuboi10, Masahiro N. Machida12, Rachel Friesen13,14, Naomi Hirano9, Yumiko Oasa15, Motohide Tamura16, Yoichi Tamura16, James Di Francesco12, Kazuya Saigo1, Takeshi Kamazaki1, Yoshito Shimajiri6, Ryohei Kawabe1,2,3

1 National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan
2 The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan
3 Department of Astronomy, School of Science, University of Tokyo, Bunkyo, Tokyo, 113-0033, Japan
4 Department of Astronomy, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
5 NEC Corporation Radio Application, Guidance and Electro-Optics Division, 1-10, Nishin-sho, Fuchu, Tokyo 183-8501, Japan
6 Laboratoire AIM, CEA/DAM-CNRS-Université Paris Diderot, IRFU/Service d'Astrophysique, CEA, Saclay, F-91191 Gif-sur-Yvette, France
7 Department of Earth and Space Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
8 Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065, Japan
9 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 10617, Taiwan
10 Department of Physics, Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan
11 Department of Earth and Planetary Science, Faculty of Science, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka, 812-8581, Japan
12 NRC Herzberg Inst of Astrophysics, 5071 W Saanich Road, Victoria, BC V9E 2E7, British Columbia, Canada
13 Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada
14 North American ALMA Science Center, National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
15 Faculty of Education, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan
16 College of Science, Ibaraki University, Bunkyo 2-1-1, Mitu, Ibaraki 310-8512, Japan
17 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2018 March 30; revised 2018 September 7; accepted 2018 September 10; published 2018 October 23

**Abstract**

On the basis of various data such as ALMA, JVLA, Chandra, Herschel, and Spitzer, we confirmed that two protostellar candidates in Oph A are bona fide protostars or proto-brown dwarfs (proto-BDs) in extremely early evolutionary stages. Both objects are rarely visible across infrared (IR; i.e., near-IR to far-IR) bands. The physical nature of the cores is very similar to that expected in first hydrostatic cores (FHSCs), objects theoretically predicted in the evolutionary phase prior to stellar core formation with gas densities of $10^{11}$ cm$^{-3}$. This suggests that the evolutionary stage is close to the FHSC formation phase. The two objects are associated with faint X-ray sources, suggesting that they are in very early phase of stellar core formation with magnetic activity. In addition, we found the CO outflow components around both sources, which may originate from the young outflows driven by these sources. The masses of these objects are calculated to be $0.01-0.03 M_\odot$ from the dust continuum emission. These physical properties are consistent with that expected from the numerical model of forming brown dwarfs. These facts (the X-ray detection, CO outflow association, and FHSC-like spectral energy distributions) strongly indicate that the two objects are proto-BDs or will be in the very early phase of protostars, which will evolve to more massive protostars if they gain enough mass from their surroundings. The ages of these two objects are likely to be within $\lesssim 10^3$ years after the protostellar core (or second core) formation, taking into account the outflow dynamical times ($\lesssim 500$ years).

**Key words:** brown dwarfs – ISM: individual objects (Oph A) – ISM: jets and outflows – stars: formation – submillimeter: stars – X-rays: stars

1. **Introduction**

How a star forms is a long-standing basic question in astronomy that has been investigated extensively during the past 5 decades (Hayashi 1966; Larson 1969; Shu et al. 1987; McKee & Ostriker 2007; André et al. 2009). The widely accepted standard scenario of the formation of stars ($M_* > 0.08 M_\odot$) is the gravitational collapse of a molecular cloud core, or so-called prestellar core. Prior to the protostellar phase, the central densest part of the collapsing cloud becomes adiabatic as its density reaches $10^{11}$ g cm$^{-3}$ and its temperature becomes high enough to pause the collapse (Larson 1969). At this point, with the collapsed object in hydrostatic equilibrium, it is referred to as a first hydrostatic core (FHSC) or first core in short (Larson 1969; Masunaga et al. 1998). Its mass and radius are, respectively, $0.05 M_\odot$ and $4$ au with no rotation (Masunaga et al. 1998) and up to $100$ au with rotation (Bate et al. 2002; Matsumoto & Hanawa 2003; Saigo et al. 2008). Its predicted luminosity, $0.01-0.1 L_\odot$ (Larson 1969; Bate et al. 2002), is defined by its radius and the mass accretion rate onto its surface (Bate et al. 2002). When the core gains enough mass by accreting the surrounding gas, it evolves into a protostar. This standard scenario is sometimes called the “core accretion” model. The core accretion model assumes that a protostar is located at the center of a dense core from which the protostar obtains its mass, determining the final mass of a star formed. Another well-discussed scenario of the formation of stars is the competitive accretion model (Bonnell et al. 2000). In this model, an initially very-low-mass compact core called a stellar seed is created from the parent molecular...
clouds, and it gains additional mass from the surroundings through Bondi–Hoyle accretion.

On the other hand, substellar-mass objects such as brown dwarfs (BDs) and planetary-mass objects (PMOs; i.e., <0.08 M_{\odot}) have no widely accepted scenario for their formation (Bate et al. 2002; McKee & Ostriker 2007; Basu & Vorobyov 2012). Two possibilities are presently under debate: (1) they share the same formation pathway as stars, or (2) they undergo dynamical ejection in the star-forming disk. In the latter scenario, substellar objects can be formed in disks via gravitational fragmentation if the disks are massive and unstable; the substellar objects are then ejected through many-body interaction. Ejected objects do not accrete much material because the timescale of fragmentation and ejection is short (∼10^{3–4} years), hence less massive objects are born. Ejected dense clumps could also form BDs or PMOs if they can survive tidal disruption by being extremely dense like first cores (André et al. 2009; Basu & Vorobyov 2012). Concrete examples of forming BDs are needed for discriminating between these two scenarios.

However, the formation processes of protostars and substellar-mass objects in the earliest stage remains uncertain because there are not enough observational examples. Thus, it is important to observationally identify protostars and proto-BDs that are in the very early evolutionary stages.

The ρ Ophiuchi star-forming region is one of the best places for the study of formation of protostars and substellar-mass objects because of its proximity. Recent VLBA observations have provided an accurate distance to the ρ Ophi star-forming region (L1688) of 137 ± 1.2 pc (Ortiz-León et al. 2017). Previous distance estimates to ρ Ophi fall into the range of 120–140 pc (Knude & Hog 1998; Luhman et al. 2007; Loinard et al. 2008; Lombardi et al. 2008). Hereafter, we adopt 137 pc. Given ρ Ophi’s close proximity, we can easily achieve spatial resolution comparable to the size of our solar system (∼100 au) using currently available state-of-the-art facilities.

We observed the densest part of the Ophiuchus molecular cloud, the ρ-Ophiuchi A region (Di Francesco et al. 2004), using ALMA in 2015 and JVLA in 2012. Oph A was first observed by Ward-Thompson et al. (1989) in submillimeter continuum with UKIRT, and they named the brightest submillimeter core SM1. Later, André et al. (1993) revealed that Oph A contains several dust condensations along the filamentary ridge with JCMT and IRAM 30 m telescopes. On the basis of the Nobeyama Millimeter Array (NMA) observations at 2 mm and 3 mm, Kamazaki et al. (2001) found that SM1 includes 1″ (∼100 au) scale bright condensations. They named the brightest condensation Source-A. Source-A is also identified in 850 μm and 1.3 mm by Friesen et al. (2014) and Nakamura et al. (2012), respectively. It is also identified in N_{2}H^{+} (J = 1 – 0) as N3 by Di Francesco et al. (2004). Hereafter, we refer to source-A as SM1-A, taking into account the previous identifications based on the dust emission.

In the present paper, we discuss the physical properties of two protostellar candidates in Oph A from the ALMA and JVLA observations toward the region and also X-ray, IR, and radio data of the ρ Ophiuchi star-forming region. The two are SM1-A and a dust continuum source (hereafter referred to as Source-X) located between SM1-A and VLA 1623, which is an archetypal Class 0 protostar (André et al. 1993). The former was identified with a protostellar candidate with faint X-ray emission (Friesen et al. 2014). The latter source was recently detected in 3 mm with ALMA by Kirk et al. (2017) as core No. 10. Its compactness indicates that it is a protostellar candidate. It is worth noting that Source-X is visible as local peaks in the 350 and 450 μm maps of André et al. (1993). Here we propose that these two protostellar candidates are bona fide protostars or proto–brown dwarfs.

## 2. Observations and Data Analysis

We used the (sub)millimeter, infrared, and X-ray observation data to identify the substellar-mass objects. The millimeter and submillimeter data were mainly obtained by our ALMA Band-6 mosaic observations in Cycle-2 and JVLA 41 GHz observations. We also analyzed ALMA archive data, which were Cycle-0 Band-7 and Cycle-2 Band-6 data, for high-angular resolution imaging and determining spectral energy distribution (SED) of the candidates. At the wavelengths of NIR, Spitzer Infrared Array Camera (IRAC) and MIPS data were retrieved to search for IR counterparts. Furthermore, we reanalyzed Chandra X-ray data taken in 2000 and merged the new data taken in 2014 to improve the signal-to-noise ratios and attempt to identify deeply embedded young stellar and substellar objects that cannot be seen even at infrared wavelengths. In the following, we describe details of these observations. Parameters of (sub)millimeter observations are summarized in Table 1.

| Freq. (GHz) | Array | Date         | R.A. (J2000) (h:m:s) | Decl. (J2000) (°:′:") | FOV (°) | Beam Size (PA) (arcsec x arcsec (°)) | ms (mJy) | Comment |
|------------|-------|--------------|----------------------|------------------------|---------|------------------------------------|---------|---------|
| 41         | JVLA  | 2012 Sep 03  | 16:26:27.4           | −24:24:08              | 73      | 0.32 × 0.15 (+11.4, 0.038          | Cycle-2 |         |
| 219        | ALMA  | 2012 Aug 17  | 16:26:39.2           | −24:24:30.688          | 29      | 0.6 × 0.34 (−89.27, 0.084          | Cycle-2 |         |
| 226        | ALMA  | 2015 Mar 01  | 16:26:27.6           | −24:23:55.0            | 180 × 120 | 1.4 × 0.92 (−81.1, 0.024          | Cycle-2 |         |
| 345        | SMA   | 2007 July 29 | 16:26:27.6           | −24:23:55.0            | 36      | 2.6 × 1.26 (−49.3, 10.5            |         |         |
| 359.2      | ALMA  | 2012 Aug 24  | 16:26:27.83          | −24:23:59.2            | 17.3    | 0.64 × 0.46 (−76.7, 0.39           | Cycle-0 |         |
| 372.4      | ALMA  | 2012 July 02 | 16:26:27.83          | −24:23:59.2            | 16.7    | 0.59 × 0.42 (−75, 1.15             | Cycle-0 |         |

Notes.

a rms noise measured at the central part of each image.

b The ALMA data ID is ADS/JAO.ALMA#2013.1.00104.S.

c Obtained with 150 points of 12 and 7 m Arrays, the ALMA data ID is ADS/JAO.ALMA#2013.1.00839.S.

d The observational parameters are the same as those of the Opt-B2 observations (Kamezaki et al. 2018).

e Nakamura et al. (2012).

f Friesen et al. (2014); the ALMA data ID is ADS/JAO.ALMA#2011.0.0396.S.
2.1. SubMillimeter Array (SMA) Observations

SM1-A was observed with the SMA\textsuperscript{19} on 2007 July 29 in its compact-north configuration over the hour angle coverage of \(-1^\circ.4\) to \(4^\circ.2\). Details of the SMA are described by Ho et al. (2004). These SMA data were originally taken for polarimetric measurements (S. P. Lui 2018, private communication). The continuum data were first published in our previous paper (Nakamura et al. 2012), which describes the details of the observing parameters. Seven out of the eight SMA antennas were used, providing projected baseline lengths from 6.8 to 125.5 m. The atmospheric transparency was good, with the 225 GHz opacity ranging from \(\sim 0.05\) to 0.09 measured at the nearby Caltech Submillimeter Observatory. The double sideband receivers were tuned with a local oscillator frequency of 340.8 GHz. The IF frequency is 5 GHz, and in each sideband the correlator covers the 2 GHz bandwidth. Observations of NRAO 530 were interleaved with the target for gain calibration, whose absolute flux density at 340 GHz was measured to be 1.4 Jy by bootstrapping from observations of Uranus. The absolute flux accuracy is \(\sim 15\%\). Strong quasars 3C273 and 3C454.3 were adopted as the passband calibrators. The raw visibility data were calibrated with an IDL-based reduction package, MIR (Scoville et al. 1993), and the calibrated visibility data were Fourier-transformed and CLEANed with MIRIAD (Sault et al. 1995).

After the normal calibration and imaging processes, a very bright compact source was identified, which enabled us to perform self-calibration. The phase-only self-calibration improved the signal-to-noise ratio of the continuum image by \(\sim 30\%\) and sharpened the image.

2.2. JVLA 41 GHz Observations

SM1-A was also observed at 41 GHz (\(\lambda = 7.3\) mm) with the Karl G. Jansky VLA (JVLA), which consists of the 27 25 m antennas. The observations were conducted on 2012 September 3 in the B configuration, covering projected baseline lengths from 80 m to 7.4 km. The correlator was configured to have 16 spectral windows with 128 MHz bandwidth each, providing in total \(\sim 2\) GHz bandwidth from 39.998–0.064 GHz to 41.884–0.064 GHz. J1256-0547, J1625-2527, and 3C286 were used for bandpass, complex gain, and flux scale calibrations, respectively. In the observing sequence, the fast switching mode between the target and the gain calibrator J1625-2527 separated at \(\sim 1^\circ\) was adopted. The total on-source integration time was 2880 s. The 7.3 mm continuum image was made with natural weighting to maximize the signal-to-noise ratio, yielding a synthesized beam size of \(0^\prime.32 \times 0^\prime.15\) (P.A. = \(11^\circ.4\)). The FOV of the JVLA 25 m antennas at 41 GHz is \(\sim 73^\prime\), and hence VLA 1623, separated by \(\sim 35^\prime\) from SM1-A, was observed simultaneously. VLA 1623 and knot-a (or VLA 1623B) were clearly detected in our observations together with SM1-A, and knot-b (or VLA 1623W) was also detected above a 3\(\sigma\) level.

2.3. ALMA Observations and Data Reduction

2.3.1. Band-7 Observations in Cycle-0

The 810 \(\mu\)m and 835 \(\mu\)m (372.4 GHz and 359.2 GHz, respectively) continuum and \(N_2H^+\) \(J = 4 \rightarrow 3\) (372 GHz) observations toward SM1-A were performed on 2012 August 24–25 in ALMA Cycle-0 (see Friesen et al. 2014). The array was in the Cycle-0 Extended configuration with projected baseline lengths between \(\sim 26\) m and \(\sim 500\) m and sensitive to maximum angular scales of \(\sim 3^\prime\). The FOV was \(\sim 18^\prime\) in diameter. Using the 26 12 m antennas, the total on-source integration time was 2400 s (4 hr including the overheads). The weather conditions were good during the observations, and the system noise temperature was in the range of 400–550 K at 372 GHz, and \(\sim 200\) K at 359 GHz. The 810 and 835 \(\mu\)m continuum data were taken from the upper and the lower sidebands of the Band-7 receivers, respectively, with four sets of 128 MHz spectral windows of the ALMA baseline correlator. The line-free channels were summed to form continuum visibility data of \(\sim 256\) MHz in bandwidth each from the 810 and 835 \(\mu\)m data. J1517-243, J1625-254, and Titan were used for bandpass, complex gain, and flux scale calibrations, respectively.

Data reduction was conducted on the Common Astronomy Software Applications package (CASA) version 4.2.2. In addition to the standard calibration procedure for ALMA data, we tried self-calibration for each of the 810 \(\mu\)m and 835 \(\mu\)m continuum data sets, since SM1-A, located near the center of the FOV, is bright enough for such calibration to work well. Only phase self-calibration was done for the data set. For the 835 \(\mu\)m image, the self-calibration was quite successful, and a signal-to-noise ratio of more than 600 was achieved. In the original image by Friesen et al. (2014), who applied the uniform weighting to the \(uv\) data to create the image, the achieved rms noise level was 2.0 mJy beam\(^{-1}\) with the FWHM beam size of \(0^\prime.45 \times 0^\prime.34\). By applying the self-calibration with natural weighting, we could achieve the rms noise level of 0.39 mJy beam\(^{-1}\), which is very close to the theoretical thermal noise expectation.

2.3.2. Band-6 Observations in Cycle-2

We obtained 219 GHz continuum data from the ALMA archive. The 219 GHz continuum observations toward VLA 1623 were obtained in 2015 for ALMA Cycle-2 program (project code: 2013.1.01004.S; S.-P. Lai). The continuum data were analyzed in the same way as the above 810 and 835 \(\mu\)m data with self-calibration. The obtained beam size is \(0^\prime.6 \times 0^\prime.34\), and the rms noise achieved is \(\sim 0.084\) mJy beam\(^{-1}\) at the center of the FOV. Uncertainty of the absolute flux density scale is \(\sim 10\%\).

2.3.3. Cycle-2 Mosaic Observations

We obtained ALMA Cycle-2 observations at 226 GHz using the 12 m Array with 150 pointings and ACA with 58 pointings to cover a \(2^\circ \times 3^\circ\) region of Oph A. We successfully obtained the combined images for the continuum and three isotopic CO \((J = 2 \rightarrow 1)\) lines: \(^{12}\text{CO}(J = 2 \rightarrow 1),\) \(^{13}\text{CO}(J = 2 \rightarrow 1),\) and \(^{18}\text{O}(J = 2 \rightarrow 1)\). The details of the observed continuum and molecular lines are summarized in Table 2. The observation parameters are the same as those of the Oph B2 observations (Kamazaki et al. 2018). The reference position of the 12 m Array and the 7 m Array was set to \((\alpha_{2000.0}, \delta_{2000.0}) = (16^h27^m26^s, 28^\circ31^\prime28^\prime\prime63),\) which is the same as that of Kamazaki et al. (2018). The \(uv\) ranges sampled in the 12 m Array and 7 m Array were data were \(12.5–348\) k\(\lambda\) and \(8.1–48\) k\(\lambda\), respectively. The minimum \(uv\) distance of the

\textsuperscript{19}The SMA 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.
combined data corresponds to 25″. We used quasars, J1517-2422 and J1733-1304, for the bandpass calibrators adopted for the 12 m Array and 7 m Array observations, respectively. We observed a quasar J1625-2527 as the phase calibrator for both arrays. We used Titan and Mars for the flux calibrations of the 12 m Array and the 7 m Array observations, respectively. For the absolute flux scale of the solar system objects (i.e., flux calibrators), we used the Butler-JPL-Horizons 2012 model.

The 12 m Array and 7 m Array data were calibrated and imaged using the CASA pipeline version 4.2.2 and version 4.5.3, respectively. We modified the scripts prepared by the ALMA observatory in which the shadowing criterion for the bandpass data was reduced from 7 to 6 m to recover some data flagged by the original scripts. Then we conducted the calibration by ourselves. In this paper, we will describe briefly a combined continuum map at 226 GHz and 12CO (J = 2 − 1) detection toward two sources of interest for comparison purposes. The synthesized beams and the sensitivities of the dust continuum and 12CO data are summarized in Table 2. In Figure 1, we present the combined 12 m Array and 7 m Array 1.3 mm continuum image of Oph A with contours of blueshifted and redshifted 12CO (J = 2 − 1) emission. We also indicate the FOVs of the SMA, ALMA Cycle-0, ALMA 219 GHz Cycle-2, and JVLA observations with circles in Figure 1.

| Continuum and Line | Rest Frequency (GHz) | ΔV (km s⁻¹) | Beam Size (PA) arcsec × arcsec (°) | Noise Level (mJy beam⁻¹) |
|--------------------|---------------------|-------------|-----------------------------------|--------------------------|
| Continuum          | 226                 | 1.4 × 0.92 (−81.1) | 0.024 (mJy beam⁻¹) |
| 12CO (J = 2 − 1)   | 230.538000          | 1.39 × 0.91 (89.0) | 0.02 (Jy beam⁻¹ km s⁻¹) |
| 13CO (J = 2 − 1)   | 220.39684           | 1.45 × 0.94 (88.0) | 0.02 (Jy beam⁻¹ km s⁻¹) |
| C18O (J = 2 − 1)   | 219.560358          | 1.45 × 0.94 (88.0) | 0.015 (Jy beam⁻¹ km s⁻¹) |

Notes. *Noise levels are measured for a 1 km s⁻¹ channel. *Here are averaged frequencies of the center frequencies of two basebands assigned for continuum observations (218 and 234 GHz). This corresponds to 1.3 mm in wavelength.

Figure 1. Fields of view for JVLA, ALMA, and SMA single-pointing observations superposed on images of Oph A in 1.3 mm continuum (color) and 12CO (J = 2 − 1) blueshifted and redshifted emission (contours) obtained from the ALMA mosaic observations with the ALMA 12 and 7 m arrays. The names of 1.3 mm detected YSOs are shown, in addition to two sources, SM1-A and Source-X. The detailed observational parameters are summarized in Table 1.

2.4. Chandra Observations

The Chandra X-ray observations were performed in May 2000 (Obs ID = 637) and in 2014 December (Obs ID = 17249), both of which include the Oph A region. The comprehensive reports for the former data set have been given by Imanishi et al. (2003) and Gagné et al. (2004). Both data sets have exposure of ~100 ks. The Oph A region was observed with the ACIS-I imaging array, which is composed of four charge-coupled devices (CCDs) that are front-side illuminated (I0, I1, I2, and I3).
After downloading both of the data sets from the Chandra X-ray Center, we did the data processing and analysis using the Chandra Interactive Analysis of Observations (CIAO) software, developed by the Chandra Science Center. We started the analysis of the latter data set (Obs ID = 17249) simply using the Level 2 events list provided by the Chandra Science Center, which was filtered on the good time intervals, cosmic X-ray rejection, and position transformation to celestial coordinates (R.A., decl.) from the more primitive Level 1 outputs (see more detail in the Chandra Analysis Guide: http://cxc.harvard.edu/ciao/guides/). As for the former data set (Obs ID = 637), we generated a new Level 2 events list by reprocessing the Level 1 output by ourselves, with updated calibration data. We merged the data taken in 2000 and 2014 to improve the signal-to-noise ratios, using the CIAO software, “reproject_obs.”

2.5. IR Data Analysis and Photometry

2.5.1. Spitzer IRAC/Multiband Imaging Photometer for Spitzer (MIPS) Data and Herschel Data

We retrieved 3.6, 4.5, 5.8, 8.0, 24, and 70 μm images obtained with the IRAC (Fazio et al. 2004) and the MIPS (Rieke et al. 2004) from the NASA/IPAC Infrared Science Archive to search for the infrared counterparts of the submillimeter sources and measure the corresponding flux densities. The basic calibrated data of IRAC and MIPS are processed through masking, flat fielding, background matching, and mosaicing using the MOPEX (MOsAicKer and Point source EXtractor) software, which is a package developed at the Spitzer Science Center for astronomical image processing. We have also analyzed the recent Herschel 70 μm data from the Herschel Science Archive, which has a higher signal-to-noise ratio than the Spitzer 70 μm image.

2.5.2. Analysis of J, H, and Ks Band Data

We observed the 7′ × 7′ field toward SM1-A in the near-infrared J, H, and Ks bands simultaneously with the near-infrared camera SIRIUS on the InfraRed Survey Facility 1.4 m telescope at the Sutherland South African Astronomical Observatory on 2004 July 7, 9, 11, 16, and October 17 and 2005 March 15, April 30, May 17, and July 6. The total integration time was 7485 s. We used NOAA’s Imaging Reduction and Analysis Facility (IRAF) software package to carry out the data reduction. We applied standard procedures of near-infrared array image reduction, including dark current subtraction, sky subtraction, and flat fielding. Photometric calibration was done with the 2MASS point sources in the same field. Identification and photometry of point sources in all frames were performed using the DAOPHOT packages in IRAF. The 3σ upper limit for source detection is $K_s > 19.5$ mag.

| Source | Telescope | Wavelength (μm) | Total Flux Density (mJy) | Peak Flux Density (mJy beam$^{-1}$) | Beam Size (PA) ($^{\circ}$) | Reference/Comment |
|--------|-----------|----------------|--------------------------|-------------------------------------|---------------------------|-------------------|
| SM1-A  | Chandra*  | (2–10 keV)     | 23 counts; 13σ           | ...                                 | 1.5                       | This paper        |
|        | IRTF/SIRIUS | 2.2           | ...                      | <0.011                              | 0.5                       |                   |
|        | Spitzer/IRAC | 3.6           | ...                      | <0.0044                             | 1.66                       | 3σ upper limit    |
|        | Spitzer/IRAC | 4.5           | ...                      | 0.031 ± 0.01                        | 1.72                       | Marginal detection|
|        | Spitzer/IRAC | 5.8           | ...                      | 0.16 ± 0.05                         | 1.88                       | Marginal detection|
|        | Spitzer/MIPS | 8.0           | ...                      | <0.31                               | 1.98                       | 3σ upper limit    |
|        | Herschel/PACS | 24            | ...                      | <2.9                                | 6                         | 3σ upper limit    |
|        | ALMA/B7     | 810           | 366 ± 4.6                | 264 ± 1.15                          | 0.59 × 0.42 (−75)         | 372 GHz           |
|        | ALMA/B7     | 835           | 327 ± 1.4                | 245 ± 0.39                          | 0.64 × 0.46 (−77)         | 359 GHz           |
|        | SMA         | 870           | 350 ± 10^a               | 336 ± 10.5                          | 2.8 × 0.9 (50.3)          | 345 GHz           |
|        | ALMA/B6     | 1300          | 118.3 ± 2.0^c            | 1160 ± 0.11^c                       | 1.4 × 0.92 (−81.1)        | 226 GHz           |
|        | NMA         | 2000          | ...                      | 84 ± 24                             | 5.2 × 13.4 (−)            | 3                 |
|        | NMA         | 3000          | ...                      | 24 ± 1.8                            | 6.2 × 3.2 (−)             | 3                 |
|        | JVLA        | 7300          | 0.608 ± 0.065            | 0.443 ± 0.038                       | 0.32 × 0.15 (11.4)        | 41 GHz            |
|        | JVLA        | 40000         | 0.125 ± 0.056            | 0.081 ± 0.017                       | 1.24 × 0.66 (−7.6)        | 4                 |
|        | JVLA        | 66000         | 0.101 ± 0.046            | 0.089 ± 0.022                       | 2.0 × 1.0 (−4.8)          | 4                 |
| Source-X| Chandra*   | (2–10 keV)     | 35 counts; 19σ           | ...                                 | 1.5                       | this paper        |
|        | ALMA/B6     | 1300          | 36.0 ± 0.78              | 21.2 ± 0.29                         | 0.6 × 0.34 (−89.27)       | 219 GHz           |
|        | ALMA/B6     | 1300          | 37.9 ± 1.1               | 35.8 ± 0.29                         | 1.4 × 0.92 (−81.1)        | 226 GHz           |
|        | ALMA/B3     | 3000          | 7.56 ± 0.86              | 7.10 ± 0.44                         | 3.5 × 1.8 (−71)           | 107 GHz, 5        |
|        | JVLA        | 7300          | ...                      | <0.014                              | 0.32 × 0.15 (11.4)        | 3σ upper limit    |
|        | JVLA        | 40000         | ...                      | <0.051                              | 1.24 × 0.66 (−7.6)        | 4, 3σ upper limit|
|        | JVLA        | 66000         | ...                      | <0.066                              | 2.0 × 1.0 (−4.8)          | 4, 3σ upper limit|

Notes. Integrated and peak flux densities for images with ALMA and JVLA were obtained with Gaussian fitting to the sources.

* Based on the X-ray observations, SM1-A and Source-X are also named as A-31 (J162627.8-242359) and A-29 (J162627.4-242418), respectively (Imanishi et al. 2003; Gagné et al. 2004).

b Peak flux density was obtained from the SMA image made using visibilities with $u > 20$ kλ.

c Integrated and peak flux densities for images at 226 GHz (made using 12 and 7 m arrays) were also obtained with the Gaussian fitting task, including “sky subtraction” in CASA, on the sources in order to remove contributions from extended structures.

References. (1) Imanishi et al. (2003); (2) Gagné et al. (2004); (3) Kamazaki et al. (2001); (4) Dzib et al. (2013); (5) Kirk et al. (2017).
Table 4
Physical Properties of SM1-A and Source-X

| Property         | Unit | SM1-A       | Source-X    | First Core$^a$ |
|------------------|------|-------------|-------------|---------------|
| Mean gas density | cm$^{-3}$ | (2.2–8.4) $\times$ 10$^{11}$ | 6.0 $\times$ 10$^{10}$ | … |
| Density          | g cm$^{-3}$ | (5.2–33) $\times$ 10$^{-13}$ | 2.4 $\times$ 10$^{-13}$ | >10$^{-13}$ |
| Radius           | au   | 21          | 27          | 4–100         |
| Mass             | $M_\odot$ | 0.026–0.14 | 0.018–0.039 | ~0.1          |
| Temperature      | K    | ~40         | ~20         | ~100          |
| Dust opacity     | index | 1.5–2       | >1.4        | ~2            |
| Luminosity       | $L_\odot$ | 0.035       | (<0.01)     | 0.01–0.1      |

Note.

$^a$ The properties of first cores listed are from Larson (1969), Masunaga et al. (1998), and Saigo et al. (2008).

3. Results

3.1. Photometry

We measured the flux densities of SM1-A and Source-X using the interferometric data available, Spitzer and Herschel data, and have summarized them in Table 3 together with the number of counts by Chandra. The flux densities are measured in the $\sim$2″ × 2″ regions of spatially resolved cases to exclude extended emission, which can be seen in the SMA visibility distribution (see also Section 3.4). Peak flux densities in units of mJy beam$^{-1}$ are given for unresolved cases. Upper limits of 3σ in mJy beam$^{-1}$ are given for non-detections.

SM1-A was not detected at 70 μm in either Spitzer or Herschel data. It was marginally detected at 4.5 and 5.8 μm. SM1-A is also associated with X-ray emission with Chandra, which is already pointed out by Friesen et al. (2014). Source-X was detected only at 219 GHz, 3 mm (Kirk et al. 2017), and X-ray with Chandra. The 3σ upper limits at $K_s$, IRAC, MIPS, and Herschel bands are almost identical to those obtained for SM1-A.

Below we summarize the observational results for SM1-A and Source-X. The parameters obtained here are summarized in Tables 4 (cores) and 5 (associated CO outflows).

3.2. Detection of Compact Cores Associated with Chandra Sources

In Figure 1, we present the combined 12 m Array and 7 m Array 1.3 mm continuum image of Oph A obtained in ALMA Cycle-2. In the image, we detected two very compact and bright 1.3 mm cores, SM1-A and Source-X, which are located between VLA 1623 and SM1-A, together with a number of less bright sources. The positions of the two cores and some other young stellar objects are also shown in Figure 1. We will describe the details of this image in a separate paper (C. Hara et al. in preparation). In the present paper, we focus on the two compact, bright cores. The JVLA 41 GHz images of the individual cores are shown in Figure 2, with contours of the ALMA 359 GHz continuum emission. We detect 41 GHz continuum emission toward SM1-A, whereas we do not detect 41 GHz continuum emission above a 3σ level from Source-X.

Detection of SM1-A with ALMA has already been reported by Friesen et al. (2014). SM1-A and Source-X were also identified from the 3 mm ALMA Cycle-2 observations (Kirk et al. 2017).
source, GY 30, found by a past CO outflow search (Kamazaki et al. 2003). The total integrated intensities of the blueshifted $^{12}$CO ($J = 3 - 2$) and $^{13}$CO ($J = 2 - 1$) emission are $26 \pm 0.55$ and $7.34 \pm 0.28$ Jy km s$^{-1}$, as summarized in Table 5. The beam-deconvolved size and the brightness temperature were measured to be $\sim 1\prime\prime 2 \times 0\prime\prime 6$ and $\sim 60$–$100$ K, respectively. The simple interpretation of the blueshifted CO emission is a very compact and low-velocity outflow from the stellar core. The lack of a redshifted counterpart is puzzling and might be due to the asymmetry in velocity structure or distribution of the molecular outflow itself. In addition, surrounding/ambient molecular material potentially could have some influence (absorption) on the outflow, especially around the systemic velocity. The mass of the outflow was estimated to be between $1.3 \times 10^{-4} M_{\odot}$ and $1.3 \times 10^{-5} M_{\odot}$, where the lower and upper boundaries are for the optically thin and thick wing emission cases, respectively. (For the wing, we obtained $\tau \sim 10$ based on unpublished single-dish $^{12}$CO ($J = 3 - 2$) and $^{13}$CO ($J = 3 - 2$) data.) Here, we assumed LTE condition, the CO fractional abundance of $10^{-4}$, and the excitation temperature of 20 K. The dynamical time is roughly $\sim 430$ yr assuming the outflow length is roughly $\sim 270 / \cos i$ au and the velocity is $3 / \sin i$ km s$^{-1}$ ($i$ is measured from the plane of sky) and $i = 45^\circ$. Note that even if $i = 75^\circ$, the time is still as short as $\sim 550$ year. This outflow would be one of the most compact molecular outflows known. The inferred mass loss rate, $10^{-6} - 10^{-7} M_{\odot}$ yr$^{-1}$, is consistent with that expected from a typical low-mass protostar (e.g., Tomisaka 2002; Hara et al. 2013).

| Property                  | Unit       | SM1-A          | Source-X       | BD Model$^a$ |
|---------------------------|------------|----------------|----------------|-------------|
| $^{12}$CO(2-1) intensity  | Jy km s$^{-1}$ | $7.34 \pm 0.28$ | $1.14 \pm 0.097$ | ...         |
| $^{13}$CO(2-1) intensity  | Jy km s$^{-1}$ | $2.7 \pm 0.14$  | $<0.1$          | ...         |
| $^{13}$CO(2-1) intensity  | Jy km s$^{-1}$ | $0.26 \pm 0.02$ | $<0.15$        | ...         |
| $^{12}$CO(3-2) intensity  | Jy km s$^{-1}$ | $26 \pm 0.55$  | ...            | ...         |
| $^{12}$CO(2-1) $T_r$ peak | K          | $62 \pm 1.6$   | $11.5 \pm 1.1$ | ...         |
| $^{12}$CO(3-2) $T_r$ peak | K          | $104 \pm 8.1$  | ...            | ...         |
| Outflow velocity          | km s$^{-1}$ | $\sim 3$       | $\sim (5-10)^b$ | $\sim 2$ km s$^{-1}$ |
| Size                      | au         | $274$          | $571$          | $\sim 350$ au$^c$ |
| Dynamical time            | year       | $434$          | $\sim (285-628)^b$ | $500^d$ |
| Outflow mass $M_o$        | (1.3–3.9) \times 10^{-4} | (1.6–2.5) \times 10^{-5d} | $\sim 2 \times 10^{-3}$ |
| Mass loss rate $M_o$ yr$^{-1}$ | $(0.3–0.7) \times 10^{-6}$ | $(0.2–0.7) \times 10^{-7}$ | $\sim 4 \times 10^{-6}$ |

Notes. $^{13}$CO image around Source-X is rather affected by the strong emission in the vicinity of VLA 1623 and SM1, especially at $V = 2$ km s$^{-1}$, and the upper limit to the $^{13}$CO intensity of the outflow component seen in $^{13}$CO is a tentative value obtained from the rms noise at $V_{lsr} = 7$ km s$^{-1}$. $^a$ Quantities listed here are taken from Machida et al. (2009), in which a proto–brown dwarf with $\sim 50 M_{\jup}$ has an age of $<500$ years. $^b$ Obtained for $i = \pm (15–30)$ degree for both blue and redshifted components. $^c$ We assumed the physical quantities at the age of 500 years. $^d$ Obtained using $^{12}$CO ($J = 2 - 1$) intensity assuming $T_{ex} = 30$–$60$ K, and the opacity is $\sim 10$.

Figure 2. ALMA 359/219 GHz (contours) and JVLA 41 GHz (color) images. (left) SM1-A images at 359 GHz and at 41 GHz. (right) Source-X images at 219 GHz and 41 GHz. The color bar for 41 GHz images is shown. Contours levels are 20%, 40%, 60%, and 80% of each peak; the peaks are 245 mJy beam$^{-1}$ with $\sim 600$σ for 359 GHz image, and 21.2 mJy beam$^{-1}$ with $\sim 80$σ for 219 GHz image. The 41 GHz peak of SM1-A is $0.443 \pm 0.038$ mJy beam$^{-1}$. Source-X is not detected above $3\sigma$ at 41 GHz ($3\sigma$ upper limit is 0.114 mJy beam$^{-1}$). Positions of Chandra X-ray sources are obtained from the combined X-ray image, which are indicated with the red crosses. ALMA and JVLA beams are shown as white ellipses; the smaller one is for JVLA.

Table 5

Outflow Properties of SM1-A and Source-X
3.3. Source X

The $^{12}$CO ($J = 2 - 1$) integrated intensity contours superimposed on the 219 GHz continuum image are shown in Figure 6. We detected faint blueshifted and redshifted emission in $^{12}$CO ($J = 2 - 1$) to the $\sim 4''$ northeast of Source-X, roughly perpendicular to the elongation of dust emission at 219 GHz. Although there is no southwestern counterpart in the $^{12}$CO ($J = 2 - 1$) emission components, a possible interpretation of these components is that they are the high-velocity outflow components from Source-X, and the outflow axis is almost parallel to the plane of sky. If this emission is indeed a low-velocity outflow, then we could compute the outflow parameters of Source-X, which are listed in Table 5. The total integrated intensity of the $^{12}$CO ($J = 2 - 1$) emission is estimated to be $1.14 \pm 0.097$ Jy km s$^{-1}$, which is smaller than that of SM1-A. The outflow mass is only $10^{-3} M_\odot$ and the mass loss rate is evaluated to be about $10^{-7} M_\odot$ yr$^{-1}$.

3.4. SED

Figure 7 shows the SEDs of SM1-A and Source-X. There are several detections of cm to sub-mm emission toward SM1-A, but only two detections at 219 and 226 GHz toward Source-X. The 3$\sigma$ upper limits to NIR to FIR flux densities in Source-X are the same as those in SM1-A. The tentative detections in 4.5 and 5.8 $\mu$m are only 3$\sigma$ upper limits in SM1-A.

We compare the SED of SM1-A with the theoretical model of the first core in Figure 7. The SED of SM1-A looks similar to that of the first core, indicating that SM1-A is in the extremely early phase close to the first core formation phase.

3.5. Source Size Analysis

The source size can be derived from the beam-deconvolved size of the millimeter and submillimeter continuum emission. For SM1-A and Source-X, the beam-deconvolved sizes derived from the 359/219 GHz images (Figure 2) are $0''3 \times 0''3$ and $0''6 \times 0''3$, respectively. The beam-deconvolved size is also derived to be $0''2 \times 0''2$ from the $41$ GHz image for SM1-A. Another method to determine size is visibility fitting, assuming that the source intensity has an axisymmetric Gaussian distribution. For the assumption, we adopt the following relation:

$$\frac{UV_{1/2}}{100 \, k\lambda} \left( \frac{\Theta_{\text{FWHM}}}{1 \, \text{arcsec}} \right) = 4 \ln 2 \frac{360 - 3600}{2 \pi \times 10^5} \approx 0.9111,$$

where $UV_{1/2}$ is the uv distance where the visibility amplitude is a half of the peak, and $\Theta_{\text{FWHM}}$ is the source size (FWHM) in the image plane. In Figure 8, we show the visibility plots of SM1-A. We also compared the 359 and 41 GHz visibility distributions with those expected for the first core model (Tomida et al. 2010). The 3D radiative hydrodynamics (RHD) calculation started from critical Bonnor-Ebert (BE)–like spheres as an initial condition, which have $T = 10$ K, and densities increased by a factor of 1.6 to make them unstable. The calculations were done for initial clouds with masses of $M = 0.1$ and $1.0 M_\odot$. The SEDs and visibility distributions were calculated for inclination angles of 60°, and those for the $0.1 M_\odot$ model giving the better fits to the observations are shown in Figures 7 and 8.

The obtained source diameters from the visibility amplitude fitting of SM1-A are $0''3$ (41 au) and $0''17$ (23 au) for 359 GHz and 41 GHz, respectively. The source diameters derived from the visibility analysis agree well with the beam-deconvolved sizes in the image domain at the same frequencies. There is a large discrepancy between the diameters derived from 359 and 41 GHz, which is likely to originate from the different optical depths (The 359 GHz emission of SM1-A is likely to be optically thick, whereas the 41 GHz emission is optically thin. See Section 4.1.1 for more detail.) The source size is a half that of Friesen et al. (2014), who derived the effective radius of 42 au, where we corrected the difference in the assumed distance.

For Source-X, we do not have enough visibility data to do the same analysis as was done for SM1-A. We adopt the geometric mean of the beam-deconvolved size, $0''4$ (55 au), as the source size of Source-X. Kirk et al. (2017) measured the deconvolved size of $1''08 \times 0''36$ for Source-X, which is slightly larger than our estimate.

3.6. X-Ray Properties; $N_H$ and $L_X$

From the merged data, we made averaged source spectra, the response files, and the background files for SM1-A and Source-X, using the CIAO software “combine_spectra.” Both of the source regions are a circle with radius of 3 arcsec, centered at the respective sources. A common background region was used for both sources, taken from a source-free region in a circle with radius of 37 arcsec, centered at $(\alpha_{2000.0} = \delta_{2000.0} = (16^h26^m29^s390, -24^d24'52''94')$. The background region is located at the same CCD chip, which both sources are on.

We fitted the spectra using the thin thermal plasma model (the Astrophysical Plasma Emission Code; Smith et al. 2001), along with the photoelectric absorption model (WABS; Balucinska-Church & McGammon 1992). In the photoelectric absorption model, we adopted the Wisconsin cross-sections (Morrison & McCammon 1983) and the Anders & Ebihara (1982) relative abundances. The metal abundances and the plasma temperatures were fixed to 0.3 solar and 5 keV, respectively, based on the previously derived values for young stellar objects (e.g., Imanishi et al. 2001). The best-fit values of
Figure 5. Contour maps of blueshifted emission in $^{12}$CO ($J = 2 - 1$), $^{12}$CO ($J = 3 - 2$), $^{13}$CO ($J = 2 - 1$), and $^{18}$O ($J = 2 - 1$) for SM1-A; $V_{\text{LSR}} = -1$ to 2 km s$^{-1}$. The continuum image at 359 GHz is superposed. Contour levels are 10%, 20%, 40%, 60%, 80% of peak (3.56 ± 0.094 Jy beam$^{-1}$ km s$^{-1}$) for $^{12}$CO ($J = 2 - 1$); 20%, 40%, 60%, 80% of peak (18.5 ± 0.55 Jy beam$^{-1}$ km s$^{-1}$) for $^{13}$CO ($J = 3 - 2$); and 30%, 60%, 90% of peaks for $^{12}$CO and $^{18}$O. Peaks are 0.81 ± 0.032 Jy beam$^{-1}$ km s$^{-1}$ and 0.182 ± 0.009 Jy beam$^{-1}$ km s$^{-1}$, respectively. Beam sizes are shown as ellipses, with a smaller white ellipse indicating the beam at 359 GHz.
Figure 6. Images of blueshifted (blue line) and redshifted (red line) emission in $^{12}\text{CO}$ ($J = 2 - 1$) for Source-X; $V_{\text{lsr}} = 2 \text{ km s}^{-1}$ and 7 km s$^{-1}$ with a velocity width of 1 km s$^{-1}$ for each. The continuum image (color) at 219 GHz is superposed. Contour levels are 3, 5, and 7σ ($1\sigma = 0.04 \text{ Jy beam}^{-1} \text{ km s}^{-1}$) for each. Flux density scale is shown on the right. Beam sizes are shown as ellipses, with white ellipses indicating the beam at 219 GHz.

Figure 7. Observed SEDs for SM1-A and Source-X, together with two model SEDs for SM1-A and one model for Source-X. Filled red circles (SM1-A) and a black square (Source-X) with error bars of ±1σ are detections above 3σ, and filled blue circles and black squares with arrows are 3σ upper limits at, for example, Ks, IRAC 3.6/8 μm, Spitzer 24 μm, and Herschel 70 μm. We used the photometry data summarized in Table 2. The models are the calculated SED for a rotating first core model (dotted line) and a uniform temperature core model (light green line for SM1-A, or red broken line for Source-X). The first core SED is obtained for the aperture $r < 120 \text{ au}$ (2″ in diameter). Recently, Kirk et al. (2017) detected Source-X in 3 mm in ALMA Cycle-2 observations. Their source No. 10 corresponds to Source-X, whose flux density is 7.56 mJy at 3 mm.
the absorbing columns and the absorption-corrected X-ray luminosities in the 0.5–10 keV band, with the errors for them in 90% confidence level, are \( (N_H, L_X) = (3.0^{+0.2}_{-0.2} \times 10^{23} \text{ cm}^{-2}, \ 0.75^{+1.0}_{-0.5} \times 10^{39} \text{ erg s}^{-1}) \) and \( (3.4^{+3.7}_{-2.1} \times 10^{23} \text{ cm}^{-2}, \ 0.78^{+2.1}_{-0.6} \times 10^{39} \text{ erg s}^{-1}) \) for SM1-A and Source-X, respectively.

4. Discussion

4.1. SED Fit and Derivation of Physical Properties

4.1.1. SM1-A

The most remarkable new finding is that SM1-A is extremely dense and has an optically thick surface at 359 GHz with a radius of \( r \sim 21 \text{ au} \), as derived below. First, the SED fit with a uniform dust temperature \( (T_d) \) source model with a radius \( 0''15 \) \( (=21 \text{ au}) \) was taken to derive \( T_d \), the optical depth at 7.3 mm \( (41 \text{ GHz}) \) \( \tau_{41} \), and the dust opacity index \( \beta \). The 7.3 mm continuum emission is assumed to arise from the thermal dust emission, without free-free contamination. These parameters allow us to infer the luminosity, mass, and density of the core. We fit the observed SED using the following equations to estimate \( T_d \).

\[
S_{\nu} = (B_{\nu}(T_d) - B_{\nu}(T_{bg}))(1 - \exp(-\tau_{\nu}))\Omega,
\]

where \( T_{bg} \) is the temperature of the cosmic background radiation and set to 2.7 K. \( \Omega \) is the source solid angle for SM1-A, which is assumed to be \( 2.4 \times 10^{-12} \text{ sr} \) (corresponding to a source diameter of 41 au) at both 41 and 359 GHz for simplicity. The function \( B_{\nu}(T) \) is the Planck function, and the opacity \( \kappa_{\nu} \) (Hilderbrand 1983) is expressed as

\[
\kappa_{\nu} = 0.1 \left( \frac{\nu}{10^{12} \text{ Hz}} \right)^{\beta} \text{ cm}^2 \text{ g}^{-1}.
\]

The fit to its SED—that is, the obtained flux densities at 7.3 mm and 835 \( \mu \text{m} \) (359 GHz) together with the 24 \( \mu \text{m} \) and 70 \( \mu \text{m} \) 3\( \sigma \) upper limits—gives us \( T_d = 40 \text{ K}, \beta = 1.5–2, \) and \( \tau_{41} = 0.18. \) The optical depth at 835 \( \mu \text{m} \) is expressed as \( \tau_{835} = (7.3/0.835)^{\beta} \times \tau_{41}, \) hence \( \tau_{835} = 5–14. \) This value indicates that SM1-A has an optically thick surface at submillimeter wavelengths—that is, a submillimeter photosphere—at \( T_d = 40 \text{ K}. \) On the other hand, the optical depth at 41 GHz is much smaller than unity (i.e., SM1-A is optically thin). The object presumably has centrally condensed density distribution. The optically thin 41 GHz emission can trace the inner denser region, which cannot be seen at the optically thick 359 GHz. This would be the reason why the estimated source size at 41 GHz is smaller than that at 359 GHz.

Second, we estimate the luminosity and density of the core, where we assume a uniform-density spherical core with the opaque surface at \( r = 21 \text{ au} \) and a temperature of 40 K. The luminosity of SM1-A calculated as such is \( 0.035 L_\odot \), directly

Figure 8. ALMA, SMA, and JVLA visibility amplitudes for SM1-A. The SMA visibility amplitudes at 870 \( \mu \text{m} \) (filled green square), ALMA 835 \( \mu \text{m} \) (filled blue square), and JVLA 7.3 mm (filled red square) are plotted as a function of \( \nu \) distance, together with the rotating first core models from RHD calculations (Saigo & Tomisaka 2009; Tomida et al. 2010) for \( i = 60° \) in the late evolutionary phase. Light blue and orange lines are for an initial cloud mass of the 0.1 \( M_\odot \) giving a better fit to the data for the 1 \( M_\odot \) model. The error in the vertical scale is 1\( \sigma \) standard deviation estimated in each bin of the \( \nu \) distance shown as a horizontal bar. The same models were used for calculating the model SEDs shown in Figure 6.
using

\[ L = 4\pi r^2 \sigma_{SB} T_d^4, \]

where \( \sigma_{SB} \) is the Stefan–Boltzmann constant. The opacity-corrected mass is given as

\[ M = \frac{\tau_{\nu}}{1 - \exp(-\tau_{\nu})} \frac{S_{\nu} D^2}{\kappa_{\nu} B_{\nu}(T_d)}, \]

and we estimate this to be \( 0.054 - 0.27 M_\odot \) for \( T_d = 40 \text{ K}, \beta = 1.5 - 2, \) and \( D = 137 \text{ pc} \). This is in good agreement with that of Friesen et al. (2014). Assuming spherical symmetry, the mean number density and volume density are estimated to be \( n = (2.2 - 8.4) \times 10^{11} \text{ cm}^{-3} \) and \( \rho = (5.2 - 33) \times 10^{-13} \text{ g cm}^{-3} \), respectively, which meet those expected for a first core (Masunaga et al. 1998; Bate et al. 2002; Saigo et al. 2008; Tomida et al. 2010, 2013). In addition, the luminosity, 0.035 \( L_{\odot} \), is mostly in the range of that predicted for a first core (\( L_{\text{crit}} < 0.06 L_{\odot} \)). For comparison, we list the physical quantities of the first core predicted from numerical simulations in Table 4 (Larson 1969; Masunaga et al. 1998; Saigo et al. 2008). This similarity in physical quantities between SM1-A and the first core models indicates that SM1-A is extremely young object. Taking into account the fact that molecular outflows and X-ray emission are detected, SM1-A is likely to be an extremely young proto-brown dwarf or protostar that already has a second core inside (i.e., an extremely young Class 0 object).

4.1.2. Source-X

Source-X is lacking data to constrain its physical nature due to its limited detection at 100/219/226 GHz. Instead of modeling, we assume \( T_d = 20 \text{ K} \) (\( T_b \sim 12 \text{ K} \) is obtained for the source at 219 GHz, and \( T_d \) should be higher than that if the emission at 219 GHz is not optically thick.) In addition, we assume \( \beta = 1.5 - 2 \) since the spectral index between 219 and 41 GHz is larger than 3.4. These assumptions and the observed properties yield a mass range of \( M = 0.018 - 0.039 M_\odot \) and a number density of \( n \approx 6.0 \times 10^{10} \text{ cm}^{-3} \). Kirk et al. (2017) derived the mass of 0.071 \( M_\odot \), in 3 mm, somewhat larger than our estimation, but these are consistent with each other, taking into account the effects of the different parameters. These values are also consistent with those predicted by the first core model. This indicates that the current evolutionary phase of Source-X is similar to that of SM1-A.

The derived physical parameters of Source-X are listed in Table 5.

4.2. Comparison of X-Ray Properties among YSOs in Oph

The absorbing column densities (\( N_H \)) and absorption-corrected X-ray luminosities (\( L_X \)) for SM1-A and Source-X are plotted in Figure 9. The values for YSOs in Oph reported by Imanishi et al. (2003) are also plotted, after conversion of the X-ray luminosity using an updated distance of 137 pc. The errors for the X-ray luminosities of the YSOs are not indicated, because Imanishi et al. (2003) did not provide the errors of the X-ray luminosities. Interestingly, the derived X-ray luminosities of SM1-A and Source-X are almost the same level of those for Class II type BDs, although they are not inconsistent with the other types (e.g., Class II non-BDs).

The column density of absorbing material derived from the X-ray emission is \( \sim 3 \times 10^{23} \text{ cm}^{-2} \), the highest among Class-I Chandra sources in the Oph region. This is more evidence that the sources are extremely young Class 0 objects. On the other hand, column densities are estimated to be an order of \( 10^{25-26} \text{ cm}^{-2} \) from the obtained masses or number densities, assuming the cores are spherically symmetric and uniform in density (e.g., a core density of \( \sim 10^{11-12} \text{ cm}^{-3} \) and a core radius of \( \sim 20 \text{ au} \) [\( 3 \times 10^{14} \text{ cm} \) produce the column density to the central stellar core, \( \sim 3 \times 10^{25-26} \text{ cm}^{-2} \)]. This discrepancy between X-ray and mm/sub-mm estimates will be reconciled if the cores have not spherically symmetric but disk-like structures where column densities decrease rapidly as viewing angles changing from edge-on to pole-on. In fact, Source-X seems to have a disk-like structure perpendicular to the outflow since the beam deconvolved size of the 219 GHz image is \( 0.6 \times 0.3 \text{ with PA = } 124^\circ \), as noted in Section 3.5. According to theoretical studies (e.g., Saigo et al. 2008; Bate 2010), a centrifugally supported disk as a remnant of the first core remains even after the stellar core formation in a rotating core. The extremely dense cores in SM1-A and Source-X would be such remnants of the first cores surviving in extremely young Class 0, which can be detected in X-ray due to preferable viewing angles with less absorbing column densities.

4.3. Are SM1-A and Source-X Proto-Brown Dwarfs?

As we shown previously, we discovered two extremely young Class 0 objects with substellar masses. The fates of these low-mass objects remain uncertain. Taking into account the masses derived from the dust continuum emission, they can potentially evolve into brown dwarfs unless they gain significant masses from the surroundings. There are at least two widely discussed scenarios for brown dwarf formation (Machida et al. 2009; Basu & Vorobyov 2012). One is the gravitational contraction of a very-low-mass core. This scenario considers that brown dwarfs form similar to low-mass stars. Starting from a spherical magnetized core with 0.22 \( M_\odot \), Machida et al. (2009) demonstrated that brown dwarfs can form from such a low-mass dense core. Another scenario is the dynamical ejection from multiple systems (e.g., Reipurth & Clarke 2001) or circumstellar disks (e.g., Basu & Vorobyov 2012). Here, we briefly discuss the possibility that these objects evolve into brown dwarfs on the basis of the two scenarios.

4.3.1. Comparison with Machida et al. (2009)

Machida et al. (2009) performed 3D MHD simulations of the brown dwarf formation (see also Machida et al. 2008). Their initial condition was a critical Bonner–Ebert sphere of masses of 0.22 \( M_\odot \). For SM1-A and Source-X, the dynamical times of the outflows are estimated to be \( \sim 500 \text{ years from the second core formation epoch. In the model by Machida et al. (2009), the outflow mass and mass loss rate are derived to be } \sim 2 \times 10^{-3} M_\odot \text{ and } \sim 4 \times 10^{-6} M_\odot \text{ yr}^{-1} \text{, respectively, at the evolution time of } \sim 500 \text{ years from the first core formation epoch. The luminosity is estimated to be } 0.2 - 1.0 L_\odot \text{ with a radius of } 2 R_\odot. \text{ The outflow mass and mass loss rate are significantly larger than those obtained from the observations. If SM1-A and Source-X formed from compact dense cores, their evolution seems to be consistent with this numerical simulation.}
4.3.2. Possible Ejection from a VLA 1623A Protostellar Binary

According to the dynamical time of the molecular outflow detected, the ages of the two sources are likely to be 500–1000 years or less after the central stellar core formation. Such very young sources should be very rare even in the Oph star-forming region, hence it will be very unusual that two are independently formed and located closely in the small ∼5000 au region. It should be noted that similar types of sources are not detected via similar ALMA 149-pointing imaging in the Oph B2 region (Kamazaki et al. 2018). One possible common origin of the two sources could be ejections from the VLA 1623 region.

Reipurth & Clarke (2001) proposed that a possible observational test of the ejection scenario is to search for brown dwarfs the vicinity of Class 0 sources with an age of ∼10^4–5 years. If stellar embryos or first core–like dense gas cores are ejected from the Class 0 object in the phase of disk/envelope fragmentation, one might expect to detect one or more (proto) brown dwarfs around the Class 0 object. The apparent separations from the Class 0 object VLA1623A to SM1-A and Source-X are ∼5000 au and 2600 au, respectively. The two sources, SM1-A and Source-X, are located at PA = 30°–50°, measured from VLA1623A, and mostly aligned with the orbital plane of the disk-like envelope seen in C^{18}O (PA = 32°; Murillo et al. 2013). If we assume their ejection velocity to be roughly 3 km s^{-1}, a factor of ∼1.5 higher than the rotating velocity of the innermost in the envelope, 2 km s^{-1}, and also assume the travels are along the plane of sky, the dynamical times to travel to the current locations are estimated to be 8000 years and 4000 years for SM1-A and Source-X, respectively. If the two objects are moving at 60° to the plane of sky, the timescale is doubled but still roughly consistent with the age of the Class 0 object.

Unexpectedly, VLA1623A was resolved to two sources separated by 0"2 (∼25 au), with the recent ALMA observations (Haris et al. 2018) and our JVLA 7 mm observations (see Figure 10) suggesting an equal-mass (∼0.05–0.1 M_☉) protostellar binary. The disk-like structure in C^{18}O is likely to be a common envelope of the binary. The binary would be evidence for disk fragmentation. Each mass of the binary seems to be larger than SM1-A and Source-X; hence the binary could eject the third less massive object in the system (e.g., Reipurth & Clarke 2001). These observations seem to be consistent with the ejection scenario, especially the hybrid scenario (Basu & Vorobyov 2012); first core–like dense clumps are ejected, and the ejected clumps form very-low-mass stars afterward. It is noted that the discrepancy between the traveling times of SM1-A and Source-X and the dynamical timescales of the outflow would be reconciled with the hybrid scenario—that recent (∼1000 years) second collapses in ejected first core–like clumps triggered outflow and X-ray activity. Furthermore, Tomida et al. (2010) showed with radiation hydrostatic simulations that first cores formed in very-low-mass cores live longer than 10^4 years. If ejected cores evolve similar to such
first cores, they can travel 6000 au at $v = 3 \text{ km s}^{-1}$ in $10^3$ years.

However, further observations are required to pursue the ejection scenario more quantitatively and carefully. Some clumps may be tidally disrupted during ejection and disperse according to the simulation (e.g., Basu & Vorobyov 2012; Stamatellos & Whitworth 2009). Such failed cores may be found around VLA1623A, and tidally formed arms as fossil of interaction may also be detected, even around SM1-A and Source-X in the more sensitive observations. Since the eastern area of VLA 1623 has no significant dense gas, the other ejected objects might be found from future high-angular resolution, high-sensitivity observations.

5. Summary

Based on SMA, ALMA, JVLA, and Spitzer data, we have discovered two candidates of forming brown dwarfs or low-mass stars in the Ophiuchus A region. Detections of small outflow lobes and X-ray emission imply that they are in the extremely early formation phases of protostars or proto-BDs. The similarity in the physical nature to the FHSCs indicates that they just passed the FHSC formation phase.

We summarize the primary results of the present paper as follows:

1. We analyzed submillimeter, infrared, and X-ray data of two bright and compact dust continuum sources in Oph A, and compiled their SEDs. One, SM1-A, is located in the densest part of the Oph A ridge, and previously named SM1. We call the core SM1-A. The other, Source-X, is located south of SM1-A.

2. Both objects are mostly invisible in infrared, but are seen in X-ray, with time-variability in Source-X. This detection indicates that these objects have already experienced second core collapse.

3. We detected possible CO outflow lobes for both cores. For SM1-A, we detected high-velocity blueshifted components in $^{12}\text{CO} (J = 3 - 2)$, $^{12}\text{CO} (J = 2 - 1)$, $^{13}\text{CO} (J = 2 - 1)$, and $^{18}\text{O} (J = 2 - 1)$. For Source-X, we detected faint blueshifted and redshifted lobes in $^{12}\text{CO} (J = 2 - 1)$. The dynamical timescales of the outflows were estimated to be several hundred years for both sources.

4. From the SED fits, we derived masses of 0.028–0.14 $M_\odot$ and 0.014–0.03 $M_\odot$ for SM1-A and Source-X, respectively. The number densities are estimated to be $\sim 4.6 \times 10^{11} \text{ cm}^{-3}$ and $6.0 \times 10^{10} \text{ cm}^{-3}$ for SM1-A and Source-X, respectively. The masses of these objects are substellar ($M \lesssim 0.08 M_\odot$). These values are consistent with those predicted by the first core model. Taking into account the fact that these sources show the protostellar signatures (i.e., outflows and X-ray emission), these objects presumably passed only several hundred years from the FHSC formation. We call such objects “extremely young” Class 0 objects.

5. From their SEDs, X-ray activity, and CO outflow lobes, we speculate that the two cores are proto–brown dwarfs if they gain more mass only from remnants of the first cores or will evolve into protostars after they gain more mass from surroundings. For the latter case, these two objects might be stellar seeds in the competitive accretion scenario.

We are grateful to Ken Yabuki and Yumiko Nakamura for their help on the data reduction and analysis of the Chandra X-ray data. We thank Sergio A. Dzib for providing us with the VLA data, and Kohji Tomisakia, Yuri Aikawa, Tomoaki Matsumoto, and Kazuyuki Omukai for valuable comments and discussion. We would also like to thank the referee for their valuable comments and suggestions, which improved the paper greatly. Data analysis was in part carried out on the open use.
data analysis computer system at the Astronomy Data Center, ADC, of the National Astronomical Observatory of Japan. This work was financially supported by JSPS KAKENHI grant Nos. JP17H02863 (FN), JP16H07086 and JP18K03703 (ST), and JP17K05392 (YT), and NAOJ ALMA Scientific Research grant no. 2017-04A. Y.S. received support from the ANR (project NIKASKY, grant agreement ANR-15-CE31-0017). N.H. acknowledges a grant from the Ministry of Science and Technology (MoST) of Taiwan (MoST 107-2119-M-001-029). This paper makes use of the following ALMA data: ADS/JAO.ALMA##2011.0.00396.S, ADS/JAO.ALMA##2013.1.00839.S, ALMA is a partnership of ESO, AUI/NSC and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. Facilities: ALMA, SMA, VLA.

ORCID iDs
Ryohei Kawabe https://orcid.org/0000-0002-8049-7525
Fumitaka Nakamura https://orcid.org/0000-0001-5431-2294
Yoshito Shimajiri https://orcid.org/0000-0001-9368-3143
Shigehisa Takakuwa https://orcid.org/0000-0003-0845-128X
Yohko Tsuboi https://orcid.org/0000-0001-9943-0024
Masahiro N. Machida https://orcid.org/0000-0002-0963-0872
Rachel Friesen https://orcid.org/0000-0001-7594-8128
Yumiko Oasa https://orcid.org/0000-0001-7249-6787
Motohide Tamura https://orcid.org/0000-0002-6510-0681
Yoichi Tamura https://orcid.org/0000-0003-4807-8117
Takashi Tsukagoshi https://orcid.org/0000-0002-6034-2892
David Wilner https://orcid.org/0000-0003-1526-7587

References
Alves de Oliveira, C., Ábrahám, P., Marton, G., et al. 2013, A&A, 559, A126
Anders, E., & Ebihara, M. 1982, GeCoA, 46, 2563
André, F., Basu, S., & Inutsuka, S. 2009, in Structure Formation in Astrophysics, ed. G. Chabrier (Cambridge: Cambridge University Press), 254
André, F., Ward-Thompson, D., & Barsony, M. 1993, ApJ, 406, 122
Balucinska-Church, M., & McGammon, D. 1992, ApJ, 400, 699
Basu, S., & Vorobyev, E. 2012, ApJ, 750, 30
Bate, M., Bonnell, I., & Bromm, V. 2002, MNRRAS, 322, L65
Bate, M. 2010, MNRRAS, 404, 79
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 2000, MNRRAS, 323, 785
Di Francesco, J., Andrés, P., & Myers, P. C. 2004, ApJ, 617, 425
Dzib, S. A., Loinard, L., Mioduszewski, A. J., et al. 2013, ApJ, 755, 63
Evans, N. J., II., Dunham, M. M., Jorgensen, J. K., et al. 2009, ApJS, 181, 321
Fazio, G. G.,Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Friesen, R., Di Francesco, J., Bourke, T. L., et al. 2014, ApJ, 797, 27
Gagné, M., Skinner, S., & Daniel, K. 2004, ApJ, 613, 392
Hara, C., Shimajiri, Y., Tsukagoshi, T., et al. 2013, ApJ, 771, 128
Harris, R. J., Cox, E. G., Looney, L. W., et al. 2018, ApJ, 861, 91
Hayashi, C. 1966, ARA&A, 4, 171
Hildebrand, R. H. 1983, QJRAS, 24, 267
Ho, P. I T. P., Moran, J. M., & Lo, K. Y. 2004, ApJ, 616, 1
Imanishi, K., Koyama, K., & Tsuboi, Y. 2001, ApJ, 557, 747
Imanishi, K., Nakajima, H., Tsujimoto, M., Koyama, K., & Tsuboi, Y. 2003, PASJ, 55, 653
Kamazaki, T., Nakamura, F., Kawabe, R., et al. 2018, ApJ, submitted
Kamazaki, T., Saito, M., Hirano, N., & Kawabe, R. 2001, ApJ, 548, 278
Kamazaki, T., Saito, M., Hirano, N., Unemoto, T., & Kawabe, R. 2003, ApJ, 584, 375
Kirk, H., Dunham, M. M., Di Francesco, J., et al. 2017, ApJ, 838, 114
Knude, J., & Hog, E. 1998, A&A, 338, 897
Larson, B. R. 1969, MNRRAS, 145, 271
Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJ, 675, L29
Lombardi, M., Lada, C. J., & Alves, J. 2008, A&A, 480, 785
Luhman, K. L., Joergens, V., Lada, C., Muzerolle, J., Pasucci, I., & White, R. 2007, in Protostar and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 443
Machida, M., Inutsuka, S., & Matsumoto, T. 2008, ApJ, 676, 1088
Machida, M., Inutsuka, S., & Matsumoto, T. 2009, ApJL, 699, L157
Masunaga, H., Miyama, S., & Inutsuka, S. 1998, ApJ, 495, 346
Matsumoto, T., & Hanawa, T. 2003, ApJ, 595, 913
McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Murillo, N. M., Lai, S.-P., Bruderer, S., et al. 2013, A&A, 560, 103
Nakamura, F., Takakuwa, S., & Kawabe, R. 2012, ApJL, 758, L25
Ortiz-Leon, G. N., Loinard, L., Kounkel, M. A., et al. 2017, ApJ, 834, 141
Reipurth, B., & Clarke, C. 2001, AJ, 122, 432
Rieke, G. H., Young, E. T., Engelbracht, C. W., et al. 2004, ApJS, 154, 254
Saigo, K., & Tomisaka, K. 2009, ApJ, 728, 78
Saigo, K., Tomisaka, K., & Matsumoto, T. 2008, ApJ, 674, 997
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Scoville, N. Z., Carlstrom, J. E., Chandler, C. I., et al. 1993, PASP, 105, 1482
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., et al. 2001, ApJL, 556, L91
Stamatellos, D., & Whitworth, A. 2009, MNRRAS, 392, 413
Tomida, K., Machida, M. N., Saigo, K., Tomisaka, K., & Matsumoto, T. 2010, ApJL, 723, L239
Tomida, K., Tomisaka, K., Matsumoto, T., et al. 2013, ApJ, 763, 6
Tomisaka, K. 2002, ApJ, 575, 306
Ward-Thompson, D., Robson, E. I., Whitte, D. C. B., et al. 1989, MNRRAS, 241, 119