ALMA Observations of SMM11 Reveal an Extremely Young Protostar in Serpens Main Cluster

Yusuke Aso1,2, Nagayoshi Ohashi1,2, Yuri Aikawa3, Masahiro N. Machida4, Kazuya Saigo5, Masao Saito6,7, Shigehisa Takakuwa3,4, Kengo Tomida5, Kohji Tomisaka10, Hsi-Wei Yen11, and Jonathan P. Williams12

1 Academia Sinica Institute of Astronomy and Astrophysics P.O. Box 23-141, Taipei 106, Taiwan; yaso@asiaa.sinica.edu.tw
2 Subaru Telescope, National Astronomical Observatory of Japan 650 North A ohoku Place, Hilo, HI 96720, USA
3 Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
4 Department of Earth and Planetary Sciences, Faculty of Sciences Kyushu University, Fukuoka 812-8581, Japan
5 Chile Observatory, National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
6 Nobeyama Radio Observatory, Nobeyama, Minamimaki, Minamisaku, Nagano 384-1305, Japan
7 SOKENDAI, Department of Astronomical Science, Graduate University for Advanced Studies
8 Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065, Japan
9 Department of Earth and Space Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
10 National Astronomical Observatory of Japan, Osawa, 2-21-1, Mitaka, Tokyo 181-8588, Japan
11 European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
12 Institute for Astronomy, University of Hawaii at Manoa, Honolulu, HI, USA

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Abstract

We report the discovery of an extremely young protostar, SMM11, located in the associated submillimeter condensation in the Serpens Main cluster using the Atacama Large Millimeter/submillimeter Array (ALMA) during its Cycle 3 at 1.3 mm and an angular resolution of 0.5 ~ 210 AU. SMM11 is a Class 0 protostar without any counterpart at 70 μm or shorter wavelengths. The ALMA observations show 1.3 mm continuum emission associated with a collimated 12CO bipolar outflow. Spitzer and Herschel data show that SMM11 is extremely cold (T_{bol} = 26 K) and faint (L_{bol} < 0.9 L_☉). We estimate the inclination angle of the outflow to be ~80°, almost parallel to the plane of the sky, from simple fitting using a wind-driven-shell model. The continuum visibilities consist of Gaussian and power-law components, suggesting a spherical envelope with a radius of ~0.6 au around the protostar. The estimated low C18O abundance, X(C^{18}O) = 1.5 ~ 3 × 10^{-10}, is also consistent with its youth. The high outflow velocity, a few 10 km s^{-1} at a few 1000 au, is much higher than theoretical simulations of first hydrostatic cores, and we suggest that SMM11 is a transitional object right after the second collapse of the first core.

Key words: circumstellar matter – stars: individual (SMM11) – stars: low-mass – stars: protostars

1. Introduction

Since the first hydrostatic core (FHSC) phase was theoretically predicted by Larson (1969), several FHSC “candidates” have been observationally identified based either on the lack of Spitzer infrared detections indicating low-temperature (10~30 K) or slow outflows (≤ 5 km s^{-1}), and/or chemical evolution: Cha-MMS1 (Belloche et al. 2006), L1448 IRS2E (Chen et al. 2010), L1451-mm (Pineda et al. 2011), Per-Bolo58 (Dunham et al. 2011), CB 17 MMS (Chen et al. 2012), B1-bS (Hirano & Liu 2014), and B1-bN (Hirano & Liu 2014). Nevertheless, none of these sources can be unambiguously characterized as a true FHSC, partly because the theoretically predicted parameter space of first cores is widespread; mass, lifetime, internal luminosity,^13 and radius of 0.01–0.1 M_☉, 500–5 × 10^{4} yr, 10^{−4} – 0.1 M_☉, and 5–100 au, respectively (Boss & Yorke 1995; Masunaga et al. 1998; Omukai 2007; Saigo & Tomisaka 2006; Saigo et al. 2008; Tomida et al. 2010; Commerçon et al. 2012). In addition, observations have not strongly constrained properties such as the rotation and mass accretion rate in the early phases of star formation. Simulations of rotating FHSCs suggest that those FHSCs (Bate 2011; Machida & Matsumoto 2011) can transform into Keplerian disks around protostars (Aso et al. 2015). Observationally identifying FHSCs is, therefore, important for understanding disk formation as well as star formation.

SMM11 is one of the submillimeter continuum condensations in the Serpens Main cluster-forming region (d = 429 pc; Dzib et al. 2011) identified in JCMT observations (Davis et al. 1999) and located at the southern edge of Serpens Main. A star-forming core is identified in Combined Array for Research in Millimeter-wave Astronomy (CARMA) observations (Lee et al. 2014) in 3 mm at an angular resolution of ~8″, associated with a bipolar HCN outflow with a length of ~1000 au and a velocity of ~6 km s^{-1}. They revealed that the core is located at an intersection of two filaments. Its core radius and mass were estimated from the CARMA observations to be ~900 AU and 1.35 M_☉, respectively. However, it was not detected by Spitzer (Enoch et al. 2009; Evans et al. 2009; Dunham et al. 2015) in X ray (Giardino et al. 2007) or 6 cm (Ortiz-León et al. 2015). The latter two trace magnetic activities due to convection in a second core, i.e., a protostar.

In this Letter, we report ALMA Cycle 3 observations toward a protostar, SMM11, in the associated submillimeter continuum condensation in Serpens Main in 12CO J = 2 – 1 line, C18O J = 2 – 1 line, and 1.3 mm continuum, which reveal that SMM11 is in an extremely early phase right after the second collapse.

^13 Internal luminosity does not include the luminosity due to external heating by interstellar radiation field and envelopes.
2. ALMA Observations

We observed five fields in the Serpens Main cluster, their locations based on unpublished the Submillimeter Array (SMA) data of a mosaicking survey carried out in 2010, using ALMA at its Cycle 3 stage on 2016 May 19 and 21. Observations toward the dusty core of SMM11 are reported in this Letter and those of the other four regions will be reported in future papers. The on-source observing time for SMM11 is 4.5 and 9.0 min in the first and the second days, respectively. The numbers of antenna were 37 and 39 in the first and the second days, respectively, and the antenna configuration of the second day was more extended than that of the first day. Any emission beyond 8°0 ~ 3400 AU was resolved out by ≥50% with the antenna configuration (Wilner & Welch 1994). Spectral windows for 12CO (J = 2 – 1) and 13CO (J = 2 – 1) line emissions have 3840 and 1920 channels covering 117 and 59 MHz bandwidth, respectively, at a frequency resolution of ~30.5 kHz. In this Letter, 16 and 2 channels are binned for 12CO and 13CO lines and the resulting velocity resolutions are 0.63 and 0.083 km s⁻¹, respectively. Two other spectral windows cover 216–218 GHz and 232–234 GHz, and are used to measure the continuum emission.

All of the imaging processes were performed with the Common Astronomical Software Applications (CASA). The visibilities were Fourier transformed and CLEANed with Briggs weighting, a robust parameter of 0.0, and a threshold of 3σ. Multi-scale CLEAN was used for the line maps to converge CLEAN, where CLEAN components were point sources or ~1″5 Gaussian sources.

We also performed self-calibration for the continuum data using tasks in CASA (clean, gaincal, and applycal). This improved the rms noise level of the continuum maps by a factor of ~2. These calibration tables for the continuum observations were then applied to the line data. The noise level of the line maps were measured in emission-free channels. The parameters of our observations are summarized in Table 1.

3. Results

Figure 1 shows 1.3 mm and 12CO images of the SMM11 region as well as 24 µm and 70 µm images for comparison. Strong compact emission was confirmed in 1.3 mm at the mapping center. In this Letter we call this source SMM11. The continuum emission shows a compact component and an S-shaped component surrounding the compact component. The emission is also extended in the north-south direction on a ~10״ scale, which is a part of the filaments. Two-dimensional Gaussian fitting to the 1.3 mm image provides an approximately circular deconvolved size, 160 au × 130 au (P.A. = 85°) at the distance of Serpens Main. The derived total flux density, 164 ± 1 mJy, corresponds to a total mass of 0.09–0.27 M☉ assuming a dust temperature, Tdust = 20–50 K (Harsono et al. 2015), dust opacity, κ<sub>850,μm</sub>, β = (0.035 cm<sup>2</sup> g⁻¹, 1) (Andrews & Williams 2005), and a gas-to-dust mass ratio of 100. In the northwest of SMM11, two other compact emissions separated by ≥1″ ~ 430 AU were detected beyond the primary beam, indicating the presence of a binary inside the apparently single Class I source (SSTc2d J182959.5+011159) seen in the infrared images (Figures 1(c)–(d)). The total flux density of the binary at 1.3 mm is ~8 mJy before primary beam correction. The 12CO emission traces a bipolar outflow with a size of ~6400 × 1300 AU. The 12CO emission also traces another bipolar outflow associated with the binary in the northwest of SMM11.

To quantify the evolutionary state of SMM11, we measured the flux density at near and mid-infrared wavelengths using Spitzer and Herschel. We subtracted average sky levels and then measured the flux densities in apertures twice larger than the FWHMs of the point-spread functions (PSFs; Aniano et al. 2011). The bolometric temperature, Tbol (Myers & Ladd 1993), and luminosity L<sub>bol</sub> are calculated by trapezoidal integration directly from the spectral energy distribution (SED; Figure 2) with other wavelengths in the literature, using 3σ upper limits for the integration where necessary. Figures 1(c) and (d) show that the 24 and 70 µm emission appear to be contaminated by the Class I source. Nevertheless, the derived bolometric luminosity L<sub>bol</sub> < 0.9 L☉ and particularly bolometric temperature T<sub>bol</sub> = 26 K are significantly lower than those of typical protostars (e.g., Kristensen et al. 2012). The derived bolometric luminosity 0.9 L<sub>☉</sub> is an upper limit, as its calculation includes the upper limits of flux densities.

Figure 3 shows a map of SMM11 as seen in the C<sup>18</sup>O emission. The emission is elongated along the 12CO outflow direction, showing a double peak on the eastern and western sides of the continuum peak position. The velocity gradient is overall similar to that of the 12CO outflow. The systemic velocity of SMM11 and FWHM velocity width of the C<sup>18</sup>O emission are 9.1 km s⁻¹ and 0.8 km s⁻¹, respectively, derived from a Gaussian fit to the line profile in a beam area centered on the continuum peak.
SMM11 is not detected as a point source in 70 μm, 24 μm (Figure 1), or at shorter wavelengths. Furthermore, its bolometric temperature $T_{\text{bol}} = 26$ K is in the temperature range theoretically predicted in the FHSC phase (Masunaga et al. 1998). The internal luminosity of SMM11 can also be estimated from its 70 μm flux density (Dunham et al. 2008) to be $L_{\text{int}} \lesssim 0.043 L_\odot$, which is also low enough to be consistent with theoretical predictions. We now examine whether or not this interpretation is consistent with the other observations.

### 4. Discussion

**4.1. 12CO Outflows**

The orientation angles of the eastern and western 12CO lobes were estimated to be P.A. = 79° and −110°, respectively, from symmetric axes of the integrated intensity map. Subsequently, we fitted the wind-driven-shell model (Shu et al. 1991; Lee et al. 2000) to the 12CO integrated intensity map and position–velocity diagrams along the outflow axes as described in Appendix A of Yen et al. (2017). We only used pixels within 10″ in radius because the shape of the outflow is more like a bow shock in the outer region and is not well described by the wind-driven-shell model. The fitting implies $c_0 \sin i = 1.3−1.9, i = 77°−79°$, and $v_0 = 3.4−4.0$ km s$^{-1}$ arcsec$^{-1}$ for the eastern 12CO lobe, while $c_0 \sin i = 1.7−2.7$ arcsec$^{-1}$, $i = 71°−87°$, and $v_0 = 1.6−4.0$ km s$^{-1}$ arcsec$^{-1}$ for the western 12CO lobe, where $c_0$, $v_0$, and $i$ are spatial coefficient (=z/r$^2$), velocity coefficient $(v_z/r = v_z/z)$, and inclination angle ($i = 0$ means pole-on). The best-fit parabolas are overlaid on Figure 1(b), which reproduces the overall shape of the two 12CO lobes. The inclination angle $i \sim 80°$ suggests that the outflow axes lie almost on the plane of the sky. The velocity coefficient $v_0 \sim 4$ km s$^{-1}$ arcsec$^{-1}$ suggests a dynamical time, $\sim$600 yr, and an outflow velocity of a few 10 km s$^{-1}$ at a few 1000 au, whereas theoretical simulations in the FHSC phase predict $\sim$5 km s$^{-1}$ (Machida et al. 2008; Tomida et al. 2010).

**4.2. C$^{18}$O Abundance**

The C$^{18}$O integrated intensity at the continuum peak position is 30 mJy beam$^{-1}$ km s$^{-1}$, while the continuum peak intensity is 90 mJy beam$^{-1}$. We estimated a fractional abundance of C$^{18}$O relative to H$_2$, X(C$^{18}$O), using the continuum peak intensity and a C$^{18}$O Gaussian peak intensity derived from the integrated intensity and the FWHM velocity width 0.8 km s$^{-1}$. 

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**Figure 1.** SMM11 images in line and continuum emissions. (a) 1.3 mm continuum. Contour levels are 3, 6, 12, 24... × σ. Green marks indicate young stellar object (YSO) positions (Dunham et al. 2015). Cyan circle indicates the ALMA primary beam. (b) Integrated intensity (contours) and mean velocity (color) maps of the $^{12}$CO emission, integrated from $V_{LSR} = -5$ to 23 km s$^{-1}$ except for 8–10, km s$^{-1}$ where $^{13}$CO emission is affected by self-absorption and missing flux. Contour levels are 5, 10, 20, 40... × σ, where 1σ corresponds to 24 mJy beam$^{-1}$ km s$^{-1}$. Yellow curves show the best-fit parabolic models (see Section 4.1 for more detail). (c) Spitzer 24 μm image in 1.3 mm continuum. Contour levels are 3.4 4.0 km s arcsec$^{-1}$, where 1 pixel is 3″/2 × 3″/2. Blue filled ellipses at each bottom-left corner denote ALMA synthesized beams or PSFs. X marks denote the peak position in 1.3 mm.
The dust optical depth is calculated from the continuum peak intensity, while that of the dust and C18O emitting gas is
measured (Davis et al. 1999), CARMA 3 mm (Lee et al. 2014) data. Blue points denote the measured flux density, where peak intensities in Jy beam$^{-1}$ are referred to for SHARC-II and SCUBA wavelengths. Green points denote the 3σ detection limit for IRAC data, while the upper limits at MIPS and PACS wavelengths are set to be the leaked flux densities from the neighboring protostar (SSTc2d J182959.5+011159), which are higher than three times the statistical noise levels.

Figure 2. SED of SMM11 derived from Spitzer IRAC (3.6, 4.5, 5.8, 8.0 μm), MIPS 24 μm, Herschel PACS 70 μm, CSO SHARC-II 350 μm (Suresh et al. 2016), JCMT SCUBA (450, 850 μm; Davis et al. 1999), ALMA 1.3 mm (this work), and CARMA 3 mm (Lee et al. 2014) data. Blue points denote the measured flux density, where peak intensities in Jy beam$^{-1}$ are referred to for SHARC-II and SCUBA wavelengths. Green points denote the 3σ detection limit for IRAC data, while the upper limits at MIPS and PACS wavelengths are set to be the leaked flux densities from the neighboring protostar (SSTc2d J182959.5+011159), which are higher than three times the statistical noise levels.

Figure 3. Integrated intensity map (white) and mean velocity map (color) of the C18O J = 2 − 1 emission in SMM11. Contour levels are from 3σ in steps of 3σ, where 1σ corresponds to 3.5 mJy beam$^{-1}$ km s$^{-1}$. The integrated velocity range of C18O emission is from 8.3 to 9.9 km s$^{-1}$. The X mark shows the 1.3 mm peak position, while arrows denote the directions of the C18O outflow.

The dust optical depth is calculated from the continuum peak intensity, while that of the dust and C18O emitting gas is calculated from the sum of the two peak intensities; the derived values are $\sim0.1-0.8$ when both gas and dust temperatures are 20–50 K with the same opacity and gas/dust ratio as in Section 3 under the LTE condition. The derived abundance, $X$(C18O) is $\sim(1.5-3.0) \times 10^{-10}$, is more than three orders of magnitude lower than the typical value $5 \times 10^{-7}$ in molecular clouds (Lacy et al. 1994; Wilson & Rood 1994), suggesting temperatures below CO freeze-out, 20 K, in the central 100 au. This is even lower than the overall abundance in Serpens Main (Duarte-Cabral et al. 2010) and quantitatively consistent with chemical simulations in the FHSC phase (Aikawa et al. 2012; Furuya et al. 2012). A similar depletion of the carbon-bearing molecule, H$^{13}$CO$^+$, is also reported for the FHSC candidates B1-bN and B1-bS by Huang & Hirano (2013). On the other hand, the elongation and overall velocity gradient of the C18O emission suggest molecular desorption on the eastern and western sides which may be due to heating from the associated outflow.

4.3. Continuum Visibility

Figure 4 shows various plots of the continuum visibility data. Each data point corresponds to one baseline and the visibility is averaged over one observational track, $\leq50$ min. Blue and red points denote the visibilities in the major- and minor-axes directions of the continuum image, while green points denote those in other directions. In amplitude plots (Figures 4(b) and (c)), the blue and red points mostly overlap at uv-distance greater than $\sim40–50$ m. This suggests a spherical structure with a radius of $\sim600$ au. Most of the phases are within $\lesssim 5^\circ$ from the phase reference center, i.e., the continuum peak position (Figure 4(d)). To investigate the amplitude distribution in more detail, we fitted it with three different functions: Gaussian, power-law, and a combination of the two. We find that the combination curve $0.031$ Jy exp $(-2(β/370 m)^2) + 0.089$ Jy $(β/100 m)^{0.33}$ fits the visibility profile better than the other functions, and therefore that the dust structure around SMM11 appears to consist with a compact component with a radius of $\sim70$ au and an extended, power-law component. The derived power-law index $p + q \sim 2.7$ in the outer region ($r \gtrsim 70$ au), where $p$ and $q$ are the volume density and temperature indices. The Gaussian component has an average $H_2$ number density of $\sim3 \times 10^{9}$ cm$^{-3}$ in an inner region ($r \lesssim 70$ au) if $T_{\text{dust}} = 30$ K, $\kappa_{\text{dust}} = 0.035$ cm$^2$ g$^{-1}$, and $β = 1$.

Similar analyses using continuum visibility are performed for the Class 0/I protostar L1527 IRS by Aso et al. (2017). Its bolometric temperature (44 K; Kristensen et al. 2012) suggests that L1527 IRS is more evolved than SMM11. Although L1527 IRS also shows an inclination angle close to edge-on ($\sim85^\circ$; Oya et al. 2015), its amplitude distribution shows different profiles along the major- and minor-axes, suggesting a pseudo disk-like envelope, while the envelope of SMM11 is more spherical. These may observationally imply that envelope morphology evolves from spherical shapes into more disk-like shapes.

4.4. Is SMM11 a FHSC?

The low $L_{\text{int}}$, $T_{\text{bol}}$, $X$(C18O) values and spherical envelope of SMM11 are consistent with theoretical predictions of the FHSC phase. Although $T_{\text{bol}}$ can be weakened by the inclination angle, such an effect is not significant before a disk forms (Jørgensen et al. 2009). The bolometric luminosity $\lesssim 0.9$ $L_\odot$ is much larger than the internal luminosity 0.043 $L_\odot$ due to external heating of the envelope around SMM11 and, particularly in this case, contamination from the neighboring protostar. Hence, $L_{\text{int}}$ is more directly related to the central heating source. If $L_{\text{int}}$ is due to accretion around a protostar, typical parameters indicate a very small protostellar mass, $M_{\text{ps}} \lesssim (L_{\text{int}}/0.043 L_\odot) (R/3R_\odot)/(M/1 \times 10^{-5} M_\odot$ yr$^{-1}) = 4 \times 10^{-4} M_\odot$ (Bontemps et al. 1996). Alternatively, for a typical FHSC radius and mass, the implied mass accretion rate, $\dot{M} \lesssim (L_{\text{int}}/0.043 L_\odot) (R/30 \text{AU})/(M/0.2 M_\odot) = 4 \times 10^{-5} M_\odot$ yr$^{-1}$, is consistent with expectations (Tomida et al. 2010). However, the low luminosity may be due to a low-mass accretion rate during
episodic accretion, and the stellar radius is also uncertain. Moreover, the high velocity of its outflow implies a deeper gravitational potential than predicted for FHSCs. On the other hand, two FHSC candidates reported in previous observations also have high-velocity outflows, such as L1448 IRS2E ($\sim 25$ km s$^{-1}$; Chen et al. 2010) and B1-bS ($\sim 8$ km s$^{-1}$; Hirano & Liu 2014). Furthermore, projection effects and evaluation by characteristic velocities$^{14}$ could provide lower outflow velocities than the maximum velocity for the other FHSC candidates; in fact, the characteristic outflow velocity of SMM11 is $\sim 5$ km s$^{-1}$. Hence, FHSC candidates could be divided into two groups, true FHSCs and SMM11-like protostars; the latter suggests criteria with which we can observationally identify an evolutionary phase slightly after the second collapse, where temperature, luminosity, chemistry, and morphology are still similar to those of FHSCs.

Detection limits in various wavelengths are affected by the long distance, 429 pc, of SMM11. For this reason, SMM11 requires additional observations with higher sensitivity and angular resolution than those for other similarly young protostars in order to better constrain its evolutionary phase and to establish the observational criteria.

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Figure 4. Plots of the continuum visibilities in SMM11. Red and blue circles denote data points at $\theta = 80^\circ \pm 15^\circ$ and $-10^\circ \pm 15^\circ$, respectively. (a) Data points on the $uv$-plane. (b) Visibility amplitude as a function of the $uv$-distance. The uncertainty of each amplitude is $\leq 1$ mJy. Note that the visibilities also include contributions from the binary to the northwest of SMM11, 8 mJy. (c) The same plot as (b) but in the log-log plane. (d) Visibility phase as a function of the $uv$-distance. The phase center is set to be the peak position of the continuum image. Dashed-dotted, dashed, and solid curves show the best-fit curves with Gaussian, power-law, and power-law+Gaussian functions, respectively.

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$^{14}$ Characteristic velocity is defined as the ratio of observed momentum over observed mass, or intensity-weighted mean velocity, and widely used in observational studies about FHSCs (e.g., Dunham et al. 2011) because it is less affected by sensitivity.
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Facility: ALMA.
Software: CASA, MIRIAD.

ORCID iDs
Yusuke Aso  https://orcid.org/0000-0002-8238-7709
Yasuhiko Ohashi  https://orcid.org/0000-0003-0998-5064
Yuri Aikawa  https://orcid.org/0000-0003-3283-6884
Masahiro Machida  https://orcid.org/0000-0002-0963-0872
Kazuya Saigo  https://orcid.org/0000-0003-1549-6435
Masao Saito  https://orcid.org/0000-0003-0769-8627
Shigehisa Takakuwa  https://orcid.org/0000-0003-0845-128X
Kengo Tomida  https://orcid.org/0000-0001-8105-8113
Kohji Tomisaka  https://orcid.org/0000-0003-2726-0892
Hsi-Wei Yen  https://orcid.org/0000-0003-1412-893X
Jonathan P. Williams  https://orcid.org/0000-0001-5058-695X

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