The Physical and Chemical Properties of the ρ Ophiuchi A Dense Core

Yu-Ching Chen1,2 and Naomi Hirano3

1 Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, IL 61801, USA; ycchen@illinois.edu
2 National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, 1205 West Clark Street, Urbana, IL 61801, USA
3 Academia Sinica Institute of Astronomy and Astrophysics, 11F of AS/NTU Astronomy-Mathematics Building, No.1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan

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Abstract

The physical and chemical properties of the ρ Ophiuchi A core were studied using 1.3 mm continuum and molecular lines such as C18O, C17O, CH3OH, and H2CO observed with the Submillimeter Array. The continuum and C18O data were combined with the single-dish data obtained with the IRAM 30 m telescope and the James Clerk Maxwell Telescope, respectively. The combined 1.3 mm continuum map reveals three major sources, SM1, SM1N, and VLA 1623, embedded in the extended emission running along the north–south direction, and two additional compact condensations in the continuum ridge connecting SM1 and VLA 1623. The spatial distribution of the C18O emission is significantly different from that of the continuum emission; the C18O emission is enhanced at the eastern and western edges of the continuum ridge, with its peak brightness temperature of 40–50 K. This supports the picture that the ρ-Oph A core is heated externally from the nearby stars Oph S1 and HD 147889. In contrast, the C18O intensity is lower than 15–20 K at the center of the ridge, where the continuum emission is bright. The C18O abundance decreases inside the ridge and shows anticorrelation with the N2H+ abundance. However, both C18O and N2H+ show strong depletion at the Class 0 protostar VLA 1623, implying that the dense gas surrounding VLA 1623 is colder than the freeze-out temperature of N2. The blue- and redshifted components of CH3OH and H2CO lines are seen at SM1, suggesting outflow activity of an embedded source in SM1, although the spatial distributions do not show clear bipolarity.

Key words: stars: formation – stars: low-mass – submillimeter: ISM – submillimeter: stars

1. Introduction

It is well established that the formation of low-mass stars occurs from the collapse of gravitationally bound molecular cloud cores (e.g., Shu et al. 1987). Cores before the onset of star formation are called “pre-protostellar cores” or “prestellar cores.” Physical and chemical properties of prestellar cores on the verge of star formation are particularly interesting because they provide us the clues to understand the initial conditions of star formation.

The ρ Ophiuchus cloud complex, at a distance of 137.3 ± 1.2 pc (Ortiz-León et al. 2017), is one of the closest molecular clouds with ongoing low-mass star formation. The ρ Ophiuchus main cloud L1688 consists of several regions labeled from A to F (e.g., Loren et al. 1990); among them, the ρ-Oph A core is the most prominent core in the millimeter and submillimeter continuum emission (e.g., Motte et al. 1998; Wilson et al. 1999; Johnstone et al. 2000). The continuum images show that the ρ-Oph A is a curved ridge consisting of a chain of condensations labeled SM1, SM1N, SM2, and VLA 1623. Except VLA 1623, which is a widely studied Class 0 object (Andre et al. 1993), the other condensations in the ρ-Oph A core have been considered to be starless, because there was no clear signature of star formation. However, recent high-resolution and high-sensitivity observations with the Acatama Large Millimeter/submillimeter Array (ALMA) at Band 7 have revealed that SM1 contains a spatially compact continuum emission component with a size of ~40 au (Friesen et al. 2014). Friesen et al. (2014) also claimed that SM1 is protostellar because of the X-ray and radio detection toward this source. Later ALMA observations at Band 3 discovered another compact continuum source between SM1 and VLA 1623 (Kirk et al. 2017). On the other hand, Nakamura et al. (2012) combined the data obtained with the Submillimeter Array (SMA) and the single-dish data and found additional small condensations within SM1. Their results demonstrated the importance of filling the short-spacing data in order to find the small-scale condensations buried in the extended emission.

In order to examine the evolutionary stage of the condensations, kinematic information and chemical properties provided by the molecular line observations are helpful. However, most of the interferometric observations have been limited toward the Class 0 protostar VLA 1623 (e.g., Murillo & Lai 2013; Murillo et al. 2013). In this paper, we present the 1.3 mm continuum and C18O (2–1) images obtained with the combination of the SMA and the single-dish data. Our combined images successfully recovered from large-scale to small-scale (∼5") emission from the ρ-Oph A region. We also present the SMA images of the C17O, CH3OH, and H2CO from the SM1 region.

2. Observations

2.1. SMA Data of the ρ-Oph A Ridge

The SMA data of the 1.3 mm continuum and the C18O (2–1) line were obtained from the SMA data archive. The observations were made on 2005 August 5 in the compact configuration. The primary beam size (FWHM) of the SMA 6 m antennas at 1.3 mm is 54". The ρ-Oph A ridge that is prominent in the continuum map (e.g., Motte et al. 1998) was covered with the 4-pointing mosaic (Figure 1). The spectral correlator that consists of 24 chunks of 104 MHz bandwidth covers 2 GHz bandwidth in each of the two sidebands separated by 10 GHz. The C18O line was observed simultaneously with the CO (2–1) and 13CO (2–1) lines. The spectral resolution of the chunks with
the C$^{18}$O and $^{13}$CO lines is 203 kHz per channel, which corresponds to the velocity resolution of 0.264 km s$^{-1}$. The rest of the channels are covered with the uniform resolution of 812 kHz (1.048 km s$^{-1}$). The absolute flux density scale was determined from the observations of Callisto and Uranus. A pair of nearby quasars, 1626-298 and 1517-243, were used to calibrate the relative amplitude and phase. The bandpass was calibrated by Jupiter and 3C 454.3. The visibility data were calibrated using the MIR package in IDL. The continuum data were obtained by averaging the line-free chunks of both sidebands. To improve the signal-to-noise ratio, the continuum data of the upper and lower sidebands were combined.

2.2. Single-dish Data

The 1.3 mm continuum data of the $\rho$-Oph A region were taken with the IRAM 30 m telescope by Motte et al. (1998). The observational details are described in Motte et al. (1998). The continuum image has an effective beam resolution of 13$''$ and 1$\sigma$ noise level of $\sim$10 mJy beam$^{-1}$. The single-dish data of the C$^{18}$O (2–1) line were obtained through the James Clerk Maxwell Telescope (JCMT) science archive. The C$^{18}$O observations were conducted on 1999 May 3 using the RxA3 receiver. The back end was a digital autocorrelating spectrometer that was configured to have a spectral resolution of 82.1 kHz (0.1067 km s$^{-1}$). The FWHM beam size of the JCMT at a frequency of the C$^{18}$O line is 22$''$. The 6$'$ $\times$ 6$'$ area including the entire region of the $\rho$-Oph A ridge was observed in the on-the-fly mode. The raw data were calibrated and gridded to the data cube using the “ORAC-DR” pipeline (Cavanagh et al. 2008) in the Starlink software. The resultant rms noise level of the data cube is $\sim$0.7 K per channel.

2.3. Combining Single-dish and Interferometer Data

In order to fill the short-spacing information that was not sampled by the interferometer, the SMA continuum data were combined with the IRAM 30 m data, and the SMA C$^{18}$O data cube was combined with the JCMT data cube. We used the MIRIAD package and followed the procedure described in Takakuwa (2003), which is based on the description of combining single-dish and interferometric data in Vogel et al. (1984). The combined maps were deconvolved using the CLEAN-based algorithm, MOSSDI (Sault et al. 1996). The synthesized beam is 5$''$$2 \times 3''7$ (P.A. = 6$'$1). The $\rho$-Oph A ridge was observed in the on-the-fly mode. The raw data were calibrated and gridded to the data cube using the “ORAC-DR” pipeline (Cavanagh et al. 2008) in the Starlink software. The resultant rms noise level of the data cube is $\sim$0.7 K per channel.

2.4. The SMA Observations toward SM1

The additional SMA observations toward one of the submillimeter sources, SM1, were done on 2016 March 7 and 9 in the compact configuration. The two tracks were conducted with different frequency settings, one including the CH$_3$OH (5$\nu$–4$\nu$) lines at 241.8 GHz, and the other including the
H$_2$CO (3_1,2–2_1,1) line at 225.698 GHz, H$_2$CO (3_1,3–2_1,2) line at 211.211 GHz, and C$^{17}$O (2–1) line at 224.714 GHz. The 4 GHz bandwidth in each sideband was covered by 48 chunks of 104 MHz bandwidth. The spectral resolution of the chunks with the CH$_3$OH, H$_2$CO, and C$^{17}$O lines was 204 kHz (0.264 km s$^{-1}$) per channel. The bright quasar, 3C 273, was observed as a bandpass calibrator, and the nearby quasar, 1517–243, was used as a phase and amplitude calibrator. The flux calibrators of the first track were Callisto and Ganymede, and those of the second track were Europa and MWC 349A. The visibility data were calibrated using the MIR package and imaged using the MIRIAD package. The synthesized beam sizes are 3″×2″4 for the CH$_3$OH data cube, 4″0×2″7 for the H$_2$CO (3_1,3–2_1,2) data cube, 3″3×2″4 for the H$_2$CO (3_1,2–2_1,1) data cube, and 3″7×2″5 for C$^{17}$O data cube. The 1σ rms noise level is ~0.09 Jy beam$^{-1}$ per channel in the CH$_3$OH and H$_2$CO data cubes, and that of the C$^{17}$O data cube is ~0.07 Jy beam$^{-1}$. Only the two CH$_3$OH lines with the lowest energy levels (5_0–4_0 A, $E_{\text{up}}$ = 34.8 K and 5_1–4_1, $E_{\text{up}}$ = 40.4 K) were detected. Both H$_2$CO lines (3_1,3–2_1,2; $E_{\text{up}}$ = 32.1 K and 3_1,2–2_1,1, $E_{\text{up}}$ = 33.4 K) were detected in the SMA observations, but we only present the H$_2$CO (3_1,3–2_1,2) line, since the lines having similar energy levels show similar structures. The continuum data were obtained by averaging the line-free chunks of both sidebands. The data of two sidebands were combined in order to improve the signal-to-noise ratio. In addition, the continuum visibility data of the two tracks are also combined. The synthesized beam and the 1σ rms noise level of the continuum map are 3″9×2″9 (P.A. = −9°1) and 2.7 mJy beam$^{-1}$, respectively.

3. Results and Analysis

3.1. 1.3 mm Continuum

Figure 1(a) shows the 1.3 mm continuum emission from the ρ-Oph A region obtained by the combination of the IRAM 30 m data and the SMA interferometer data. The continuum emission shows the N–S ridge similar to the single-dish map presented in Mezger et al. (1992), Andre et al. (1993), and Motte et al. (1998). There are three major components, VLA 1623, SM1, and SM1N. Our high-resolution map having an angular resolution of ~5″ reveals that each source has internal structure. The brightest source in this region is VLA 1623, a well-studied Class 0 protostar (e.g., Andre et al. 1993). The recent studies by Murillo & Lai (2013) and Chen et al. (2013) showed that VLA 1623 consists of three sources, VLA 1623A, B, and W, which are suggested to be a triple non-coeval system. In our continuum map, VLA 1623A and B, having a separation of ~1″, are not spatially resolved. On the other hand, VLA 1623-W is identified as a separate peak.

The emission from the second-brightest source, SM1, shows a well-defined peak. Recent ALMA observations at 359 GHz (Friesen et al. 2014) have revealed that this source is very compact, having a size of only 0″31 (~42 au at 137 pc). The compact source is surrounded by the extended structure having an elongation toward the northwestern direction. In the SM1 region, Nakamura et al. (2012) reported three condensations. The brightest one, a1, corresponds to the continuum peak of our map. The other two, a2 and a3, are not clearly seen in our map, probably because of the low-intensity contrast of these components and the lower angular resolution of our map. VLA 1623 and SM1 are connected by the curved emission ridge, having two local peaks labeled as VLA 1623-N1 and N2. In contrast to SM1 and VLA 1623, the northern source SM1N is spatially extended and contains no compact component, which is consistent with the 359 GHz results of Friesen et al. (2014). The emission from SM2 is less significant, because this source is located beyond the area covered by our 4-pointing mosaic. The 3 mm continuum map in Kirk et al. (2017) has a similar structure to our continuum map; both the extended filament northeast of SM1 and VLA 1623-N1 are clearly seen in their map.

Figure 2(a) shows the continuum map of the SM1 region obtained with the SMA in 2016. With higher sensitivity thanks to the wider bandwidth, two sources, VLA 1623-N1 and N2, are clearly seen in this map. The SMA data are also combined with the IRAM 30 m data (Figure 2(b)). The combined map recovers well the extended emission around the SM1 peak. The continuum emission extends to the north of SM1, which is consistent with the 340 GHz results of Nakamura et al. (2012). However, the small-scale condensations a2 and a3 reported by
Table 1

| Source               | R.A. (J2000) | Decl. (J2000) | $S_\nu$ (Jy beam$^{-1}$) | $S_\nu$ (Jy) | FWHM (arcsec) | P.A. (degrees) | Mass$^a$ ($M_\odot$) | $M_{\text{IR}}$ ($M_\odot$) |
|----------------------|--------------|---------------|--------------------------|--------------|---------------|---------------------|------------------------|-----------------------------|
| VLA 1623             | 16:26:26.44  | −24:23:30.65  | 0.50                     | 0.86         | 3′′22 × 3′′4  | 7.3                | 0.41                   | 0.010                       |
| VLA 1623-N1$^b$      | 16:26:27.38  | −24:23:18.26  | 0.049                    | 0.11         | 4′′7 × 4′′8   | 44.3               | 0.05                   | 0.014                       |
| VLA 1623-N2$^b$      | 16:26:27.15  | −24:24:24.17  | 0.06                     | 0.31         | 6′′8 × 5′′3   | 60.1               | 0.15                   | 0.02                        |
| VLA 1623-W           | 16:26:25.80  | −24:27:27.81  | 0.14                     | 0.32         | 5′′5 × 3′′4   | 14.4               | 0.15                   | 0.017                       |
| SM1                  | 16:26:27.83  | −24:23:59.34  | 0.19                     | 0.59         | 5′′8 × 4′′2   | −9.3               | 0.28                   | 0.018                       |
| SM1-W$^b$            | 16:26:27.00  | −24:23:56.61  | 0.02                     | 0.17         | 12′′2 × 4′′0  | 36.4               | 0.08                   | 0.038                       |

Notes.

$^a$ The uncertainty in the mass calculation derived from the 1σ error in the measured flux is ∼10%.
$^b$ The parameters for VLA 1623-N1, VLA 1623-N2, and SM1-W are determined from the SMA map (Figure 2(a)) only.

Nakamura et al. (2012) are not clearly seen in our maps. Instead, our SMA map shows the local intensity maximum to the west of SM1, which is labeled as SM1-W. Instead of being obvious in the SMA map (Figure 2(a)), VLA 1623-N1, VLA 1623-N2, and SM1-W are not significant in the combined map (Figure 2(b)) because of the rather high-level emission from the extended component.

The coordinates, peak flux density, total flux, size, and position angle of each source were determined from the single Gaussian component fitting using the MIRIAD task IMFIT. The size and position angle of each source are derived after being deconvolved with the beam. The parameters of VLA 1623-N1, VLA 1623-N2, and SM1-W are derived from the SMA map shown in Figure 2(a), while those of VLA 1623, VLA 1623-W, and SM1 are from the combined map shown in Figure 2(b). The derived parameters are listed in Table 1.

3.2. C$^{18}$O (2−1)

The integrated intensity map of the C$^{18}$O obtained by combining the JCMT data and the SMA data is presented in Figure 1(b). Although the C$^{18}$O emission comes from the N–S ridge of the ρ-Oph A, its spatial distribution is significantly different from that of the continuum; the C$^{18}$O emission is bright in the eastern and western edges of the ridge and rather faint at the center of the ridge, where the continuum emission is bright.

In the northern part, the anticorrelation between the C$^{18}$O and continuum is significant; the continuum peak SM1N is located between two bright ridges of the C$^{18}$O. In the southern part, there is a third ridge of C$^{18}$O emission connecting SM1 and VLA 1623. However, the C$^{18}$O does not follow the curved ridge traced by the 1.3 mm continuum. In addition, locations of the C$^{18}$O peaks do not coincide with the continuum peaks. On the other hand, the C$^{18}$O peak coincides with the continuum peak at VLA 1623-W.

Since our C$^{18}$O map contains the short-spacing information obtained with the JCMT, the lack of bright emission at the center of the ridge is not the effect of spatial filtering of the interferometer. The CO and $^{13}$CO lines observed in the ρ-Oph molecular cloud often show the self-reversal line profile, which could produce an intensity drop at the line of sight at high optical depth. However, the observed C$^{18}$O line does not show such a self-reversal profile. Such an anticorrelation between the C$^{18}$O and continuum was not clear in the previous single-dish observations (Liseau et al. 2010; White et al. 2015) owing to their angular resolutions. Recently, Liseau et al. (2015) deconvolved their C$^{18}$O (3−2) image and improved the angular resolution from 19″ to 7″. Their deconvolved C$^{18}$O image also reveals the anticorrelation with the continuum distribution. Moreover, by comparing our C$^{18}$O integrated intensity map with the N$_2$H$^+$ map from Di Francesco et al. (2004), we found that most of the N$_2$H$^+$ emission comes from the region between two C$^{18}$O ridges (Figure 3). The highest N$_2$H$^+$ emission occurs across SM1N and SM1, where the C$^{18}$O emission is missing. The spatial distribution of the C$^{18}$O is anticorrelated with that of N$_2$H$^+$ except the southern ridge including VLA 1623-N1 and VLA 1623-N2.

The C$^{18}$O peak intensity map shown in Figure 4 indicates that the prominent C$^{18}$O ridges have high brightness temperatures of ∼40 K, whereas, in the remaining region, the temperature is roughly 25 K or below. A notable thing is that, except SM1, where the temperature is roughly 40 K, major dust condensations are located in the regions with lower brightness temperature; VLA 1623-N1 and VLA 1623-N2 are in the region with ∼30 K, and SM1N, VLA 1623, and VLA 1623-W are in regions of ∼25 K.

The channel map (Figure 5) and the position–velocity map along the N–S cut through R.A. = 16h26m27.7s (Figure 6) show that there is a significant velocity gradient along the ρ-Oph A ridge. The velocity centroid in the northern part of the ridge is at $V_{\text{LSR}}$ ∼3.1 km s$^{-1}$ and gradually changes to ∼3.7 km s$^{-1}$ at the position of SM1, which is consistent with the C$^{18}$O (3−2) results of Liseau et al. (2010). The southern redshifted component shows an arc-like feature at ∼4.3 km s$^{-1}$. This arc-like feature follows the eastern edge of the continuum arc connecting SM1 and VLA 1623 (see panel 10 of Figure 5). Bergman et al. (2011) have also shown that the chemical properties are different between the northern part and southern part of the ridge. The deuterated species like HDCO, D$_2$CO, and N$_2$D$^+$ are abundant in the southern part with $V_{\text{LSR}}$ ∼3.7 km s$^{-1}$ but are deficient in the northern part with $V_{\text{LSR}}$ ∼3.1 km s$^{-1}$.

The abrupt velocity change near SM1N in the moment 1 map (Figure 7) is likely to have originated from the third component at $V_{\text{LSR}}$ ∼2.9 km s$^{-1}$, which is clearly seen in the H$_2$CO position–velocity and profile maps in Bergman et al. (2011). This component is not clearly seen in the position–velocity map of C$^{18}$O (3−2) in Bergman et al. (2011), while it is clearly seen in our C$^{18}$O (2−1) position–velocity map. Furthermore, the 2.9 km s$^{-1}$ component has the C-shaped pattern seen in the moment 1 map and channel map and might be related to the methanol-rich gas, which also shows C-shaped morphology in larger scale (Garay et al. 2002; Bergman et al. 2011). Overall, it is likely that the ρ-Oph A ridge consists of three components with different velocities and chemical properties: the northern component at 3.1 km s$^{-1}$, which is deficient in deuterated species; the southern deuterium-rich component at 3.7 km s$^{-1}$;
and the northwestern component at 2.9 km s\(^{-1}\) having high methanol abundance.

3.3. \(\text{C}^{18}\text{O}\) and \(\text{N}_2\text{H}^+\) Abundance

The column density of \(\text{H}_2\) in \(\rho\)-Oph A can be determined from 1.3 mm continuum emission by the formula

\[
N(\text{H}_2) = \frac{S_r}{\Omega_m \mu m_1 \kappa_\nu B_r(T_{\text{dust}})} \tag{1}
\]

where \(S_r\) is the 1.3 mm flux density, \(\Omega_m\) is the solid angle of the beam, \(\mu\) is the mean molecular weight, \(m_1\) is the mass of the atomic hydrogen, \(\kappa_\nu\) is the dust opacity per unit mass (assumed to be 0.005 cm\(^2\) g\(^{-1}\)), which is the same value used by Motte et al. 1998 for prestellar clumps and cores), and \(B_r(T_{\text{dust}})\) is the Plank function at the dust temperature, which is assumed to be 27 K (Andre et al. 1993).

On the other hand, by following Mangum & Shirley (2015), the \(\text{C}^{18}\text{O}\) and \(\text{N}_2\text{H}^+\) column densities can be derived from the local thermodynamic equilibrium (LTE) assumptions,

\[
N(\text{C}^{18}\text{O}) = \frac{3.15 \times 10^{15}}{\theta_a \theta_b} \left(\frac{T_{\text{ex}}}{1 - e^{-\tau}}\right) \exp\left(\frac{15.8}{T_{\text{ex}}}\right) \exp\left(\frac{10.54}{T_{\text{ex}}}\right) - 1
\]

\[
\times \left(\frac{T_{\text{ex}} + 0.75}{T_{\text{ex}} - 2.73}\right) \int S_r(Jy) dv (\text{cm}^{-2}) \tag{2}
\]

and

\[
N(\text{N}_2\text{H}^+) = \frac{4.48 \times 10^{13}}{\theta_a \theta_b} \left(\frac{T}{1 - e^{-\tau}}\right) \exp\left(\frac{4.47}{T_{\text{ex}}}\right) - 1
\]

\[
\times \left(\frac{T_{\text{ex}} + 0.75}{T_{\text{ex}} - 2.73}\right) \int S_r(Jy) dv (\text{km} s^{-1}) \text{ cm}^{-2}, \tag{3}
\]

where \(\theta_a\) and \(\theta_b\) are the major and minor axes of the beam (FWHM in arcseconds), respectively, \(T_{\text{ex}}\) is the excitation temperature, \(\tau\) is the optical depth, \(S_r\) is flux density, and \(dv\) is the velocity interval. Since \(\text{C}^{18}\text{O}\) is not optically thin in the \(\rho\)-oph A region, the optical depth of the \(\text{C}^{18}\text{O}\) emission was estimated using the \(\text{C}^{17}\text{O}\) (2-1) and \(\text{C}^{13}\text{O}\) (2-1) data observed with the JCMT (Gurney et al. 2008). Unfortunately, the \(\text{C}^{13}\text{O}\) data set covers only the 50\(^\prime\) \times 50\(^\prime\) areas centered at SM1 and VLA 1623. Therefore, we could not derive the optical depth of the \(\text{C}^{18}\text{O}\) in the SM1N region. We followed the method described in Appendix B of Ladd et al. (1998). The \(\text{C}^{18}\text{O}/\text{C}^{17}\text{O}\) abundance ratio was assumed to be 3.65 (Penzias 1981). Because the JCMT data were sampled in a 10\(^\prime\) grid, the optical depths were calculated by interpolating the data points. The calculation showed that \(\text{C}^{18}\text{O}\) is optically thick in most of the \(\rho\)-Oph A region, with the highest value of 5.5 at 5\(^\prime\) W of SM1. As for \(\text{N}_2\text{H}^+\) lines, Di Francesco et al. (2004) showed that the total optical depth of the \(\text{N}_2\text{H}^+\) line is larger than unity in the \(\rho\)-Oph A region. Therefore, the \(\text{N}_2\text{H}^+\) column density was calculated from the “isolated” 101-012 component at 93.176265 GHz with the optically thin assumption.
and divided by its relative intensity, which is 1/9. The excitation temperature of the C$^{18}$O formula in each pixel was derived from the peak intensity map (Figure 4). The excitation temperature of N$_2$H$^+$ was assumed to be 15 K, based on the result of hyperfine structure fitting in Di Francesco et al. (2004). In order to calculate the abundances, the resolution of the H$_2$ column density map derived from the continuum data was adjusted to be the same as those of the C$^{18}$O map and N$_2$H$^+$ map, respectively. After dividing C$^{18}$O column density and N$_2$H$^+$ column density by H$_2$ column density, we derived the abundance distribution over the $\rho$-Oph A region.

The C$^{18}$O abundance distribution in the $\rho$-Oph A region is presented in Figure 8, and the N$_2$H$^+$ abundance distribution in the same region is presented in Figure 9. The column densities of H$_2$, C$^{18}$O, and N$_2$H$^+$, and the abundances of C$^{18}$O and N$_2$H$^+$ at each source position are listed in Table 2 for comparison. As shown in Figure 8, the C$^{18}$O abundance decreases significantly at the central N–S ridge and the position of VLA 1623. The C$^{18}$O abundances at those regions are below $2 \times 10^{-7}$. On the other hand, the C$^{18}$O abundance value often used in the interstellar medium is $(1.7–2) \times 10^{-7}$ (Wannier 1980; Frerking et al. 1982). The higher value of $4.8 \times 10^{-7}$ is also suggested from the CO abundance of $2.7 \times 10^{-4}$ (Lacy et al. 1994; Jørgensen et al. 2005) and [^{16}O/^{18}O] = 560 (Wilson & Rood 1994). The C$^{18}$O abundance values measured in the N–S ridge and VLA 1623 are a factor of 5–10 lower than the interstellar values. On the other hand, the C$^{18}$O abundance values at SM1, VLA 1623-N1, VLA 1623-N2, and VLA 1623-W are $\sim 2 \times 10^{-7}$, which is comparable to that of the interstellar value.

The N$_2$H$^+$ abundance varies between different sources among $\rho$-Oph A. Di Francesco et al. (2004) suggest that it is due to different evolutionary stages of each source. The N$_2$H$^+$ abundance is enhanced in the northern part of the ridge and the C-shaped region including VLA 1623-N1 and VLA 1623-N2.
It drops significantly to the eastern edge of the ridge and the southwestern part including VLA 1623. It should be noted that the N2H\(^+\) abundance is very low, \(\sim 1.4 \times 10^{-11}\) at the position of VLA 1623, toward which the C18O abundance is also the lowest.

### 3.4. C\(^{17}\)O, CH\(_3\)OH, and H\(_2\)CO at SM1

The C\(^{17}\)O (2–1), which is typically optically thin, can be used to probe the high-density region near SM1. The optical depth \(\tau\) of C\(^{17}\)O in the \(\rho\)-oph A region was obtained from the calculation of the optical depth of C\(^{18}\)O in Section 3.3. The \(\tau\) (C\(^{17}\)O) has a maximum value of 1.5 at 5″ W of SM1 and is smaller than unity in most parts of the \(\rho\)-oph A region. The integrated intensity map of C\(^{17}\)O in the SM1 field is presented in Figure 10(a). The C\(^{17}\)O emission extends from SM1 through VLA 1623-N2 and VLA 1623-N1 and reaches to VLA 1623. The overall distribution of the C\(^{17}\)O follows that of the continuum emission. The C\(^{17}\)O peak at VLA 1623 coincides well with the continuum peak. On the other hand, the C\(^{17}\)O peak at SM1 appears at \(\sim 3″\) northeast of the continuum peak. The emission component at 15″ NW of SM1 is more than 17\(\sigma\), but there is no counterpart of this component in the continuum or other molecular lines. The missing flux of the C\(^{17}\)O was estimated by comparing the flux value of the SMA map convolved to the JCMT beam and that observed with the JCMT. It turned out that the C\(^{17}\)O flux recovered by the SMA is only \(\sim 3\%\) of the single-dish flux. This indicates that most of the C\(^{17}\)O emission comes from the spatially extended component and very little from the envelope of SM1.

We calculated the C\(^{17}\)O abundance from the continuum and C\(^{17}\)O data observed with the SMA by following the similar steps described in Section 3.3. The \(T_{\text{ex}}\) is assumed to be 27 K. The C\(^{17}\)O fractional abundances are \(3.6 \times 10^{-9}\), \(2.4 \times 10^{-9}\), \(2.4 \times 10^{-9}\), and \(6 \times 10^{-9}\) at VLA 1623, SM1, VLA 1623-N1, and VLA 1623-N2, respectively. After multiplying by the \(^{18}\)O/\(^{17}\)O relative abundance of 3.65 (Penzias 1981), the derived C\(^{18}\)O abundances are \(1.3 \times 10^{-8}\) at VLA 1623, \(8.8 \times 10^{-9}\) at SM1 and VLA 1623-N1, and \(2.2 \times 10^{-8}\) at VLA 1623-N2, which are significantly lower than those estimated in the previous section using the combined C\(^{18}\)O and continuum data. Because the abundance values derived here use the SMA data alone, they are the local values at the compact sources. It is likely that the C\(^{18}\)O abundance in the compact sources is more...
than one order of magnitude lower than the interstellar value, even at the positions of SM1, VLA 1623-N1, and VLA 1623-N2.

The CH$_3$OH and H$_2$CO show a localized emission peak at the position of SM1 (Figures 10(b) and (c)). These lines also show a localized peak toward VLA 1623. The CH$_3$OH shows the secondary peak at SM1-W. The CH$_3$OH emission is also seen near VLA 1623-N2. The spatial distribution of the CH$_3$OH emission correlates well with that of the continuum emission, except for the missing counterpart of VLA 1623-N1. On the other hand, the spatial distribution of the H$_2$CO is different; the emission extends to the southeast and southwest of SM1. There is no counterpart of VLA 1623-N1 and VLA 1623-N2 in the H$_2$CO map. In addition, the H$_2$CO shows very bright emission at 30’N of SM1, which corresponds to the northern edge of our field of view. This emission component is also seen in the CH$_3$OH. The location of these components corresponds to the southern edge of the $\sim 2.9$ km s$^{-1}$ component seen in the single-dish maps of H$_2$CO and CH$_3$OH (Bergman et al. 2011). Since CH$_3$OH and H$_2$CO are good tracers for molecular outflow (e.g., Bachiller et al. 2001; Gerin et al. 2015), we searched for the signature of outflow in this region. The CH$_3$OH and H$_2$CO emission was separated into the blueshifted part and redshifted part (Figure 11). Both blueshifted and redshifted components are seen in the vicinity of SM1. However, their spatial distributions do not show clear bipolarity.

### 4. Discussions

#### 4.1. Nature of the Small Condensations

Determining the fate of small condensations such as SM1, VLA 1623-N1, VLA 1623-N2, and SM1-W in the dense core will benefit the understanding of the low-mass star-forming process. The mass of each condensation is derived from the total flux listed in Table 1, using the formula

$$M_{\text{env}} = \frac{SD^2}{\kappa_{\nu}B_{\nu}(T_{\text{dust}})},$$

where $S$ is the total flux, $D$ is the distance to the source, $\kappa_{\nu}$ is the dust mass opacity, and $B_{\nu}(T_{\text{dust}})$ is the Planck function at a given temperature. The dust mass opacity $\kappa_{\nu}$ is assumed to be 0.005 cm$^2$ g$^{-1}$, which is the same as in Motte et al. (1998). The dust temperature is assumed to be 27 K (Andrè et al. 1993). The masses of these condensations are in the range of $10^{-2}$ to $10^{-1}$ $M_\odot$. For comparison, the mass of the critical Bonnor–Ebert
structure in SM1. In addition, SM1 is also associated with the source detected in X-ray and radio at 5 GHz (Gagne et al. 2004). These imply that SM1 has already harbored a protostar. VLA 1623-N1 has similar properties to SM1. This source is identified as compact emission source 10 by Kirk et al. (2017) in their 3 mm image observed with the ALMA. In addition, the position of the X-ray source, J162627.4−242418, which is one of the unidentified X-ray sources in Gagne et al. (2004), coincides with that of VLA 1623-N1. Recently, Kawabe et al. (2018) studied the properties of SM1 and VLA 1623-N1 based on the multi-wavelength observations from radio to X-ray and proposed that these sources are proto-brown dwarfs or in the very early phase of low-mass protostars. On the other hand, there is no clear counterpart of VLA 1623-N2 and SM1-W in the ALMA images at 3 mm (Kirk et al. 2017) and 1.3 mm (Kawabe et al. 2018). The 3 mm image of Kirk et al. (2017) shows some hint of faint condensation at the position of VLA 1623-N2. In order to search for the counterpart of VLA 1623-N2, we have examined the 3 mm continuum image that was made of two data sets available from the ALMA data archive. The resulting image (Figure 12 in the Appendix) has higher sensitivity and resolution than those of the 3 mm image in Kirk et al. (2017). However, our new 3 mm image does not show clear evidence of a compact source at the position of VLA 1623-N2. The 1.3 mm image presented in Kawabe et al. (2018) also does not show the corresponding source. In addition, there is no counterpart of this source in the X-ray (Gagne et al. 2004) or in the radio (Leous et al. 1991; Gagne et al. 2004).

Although the water maser source is found at R.A.(J2000) = 16°26′27″028 and decl.(J2000) = −24°24′24″284 (Yu & Chernin 1997), which is only 1.76 W of VLA 1623-N2, it is unlikely that VLA 1623-N2 harbors a protostar. Another condensation at SM1-W does not have a clear counterpart in the ALMA images of 3 mm (Kirk et al. 2017), 1.3 mm (Kawabe et al. 2018), and 0.84 mm (Friesen et al. 2014) as well. This source is not detected in the X-ray (Gagne et al. 2004) or in the radio (Leous et al. 1991; Gagne et al. 2004). The absence of a compact condensation implies that VLA 1623-N2 and SM1-W are still in the prestellar stage.

4.2. Physical Condition and CO Depletion

As shown in Figure 4, the peak intensity of the C^{18}O is enhanced to \( T \sim 40–50 \) K at the edges of the \( \rho \)-Oph A ridge, while it is lower than 30 K toward the center of the ridge. The higher temperature in the edges is likely due to external heating by stellar UV and X-ray photons. One of the possible heating sources is Source 1 (hereafter Oph S1) at \( \sim 15′ \) (12,000 au) E of SM1N. Oph S1 having a luminosity of \( \sim 1600 \) \( L_{\odot} \) (Wilking et al. 2005) is known to be a binary with a B4 primary and companion with a K magnitude of 8.3 (Simon et al. 1995) and is emitting both strong nonthermal radio and X-ray emission (Gagne et al. 2004). The UV and higher-energy photons reach the eastern surface of the \( \rho \)-Oph A ridge and heat the eastern edge of the ridge. Another heating source is the B2 star HD 147889 with \( \sim 4500 \) \( L_{\odot} \) (Greene & Young 1989), which is \( \sim 15′ (0.5 \) pc) to the southwest and behind the \( \rho \)-Oph A ridge (Liseau et al. 1999). This source is likely to be responsible in heating the ridge from the west. Since the continuum emission from mid-infrared, to far-infrared, to millimeter in the \( \rho \)-Oph A region is modeled well with the external heating of S1 and HD 147889 (Liseau et al. 2015), it is natural to consider that the molecular gas in the \( \rho \)-Oph A ridge is also heated from these two stars.

sphere (Bonnar 1956) is calculated from

\[
M_{\text{BE}} = 2.4 \frac{kT}{mg} r_c,
\]

where \( k \) is the Boltzmann constant, \( T \) is the gas kinetic temperature, \( G \) is the gravitational constant, \( m \) is the mean molecular mass, and \( r_c \) is the critical radius. The critical radius \( r_c \) is simply assumed to be the same as the semimajor axis of each source. The temperature is assumed to be 27 K, which is the same as that used in the mass calculation. As shown in Table 1, the masses of all the condensations exceed the Bonnor–Ebert mass, which implies that those condensations are gravitationally bounded.

VLA 1623 and VLA 1623-W have already been identified as a non-coeval multiple system (Murillo & Lai 2013). The recent ALMA observation by Friesen et al. (2014) also found compact
Interestingly, the N$_2$H$^+$ binary system is colder than the CO freeze-out temperature.

On the other hand, the C$^{18}$O intensity drops significantly toward the continuum ridge; especially, it is below 15 K in the region between SM1 and SM1N. In this region, the abundances of the C$^{18}$O and N$_2$H$^+$ show clear anticorrelation. Similar anticorrelation between C$^{18}$O (3–2) and N$_2$H$^+$ (3–2) is also seen in Liseau et al. (2015). These imply that the gas temperature in the center of the ρ-Oph A ridge, where the external radiation is shielded, is lower than the CO freeze-out temperature of ∼25 K (Öberg et al. 2005). In the cold and dense environment, N$_2$, a parent molecule of N$_2$H$^+$, is also expected to freeze out. Since the desorption energy ratio of N$_2$ and CO measured in the recent laboratory experiments is ∼0.9 (Öberg et al. 2005; Fayolle et al. 2016), the N$_2$ freeze-out temperature is only a few degrees lower than that of CO. The clear anticorrelation between C$^{18}$O and N$_2$H$^+$ implies that sufficient amount of N$_2$ is in the gas phase. This is probably because the area with the C$^{18}$O–N$_2$H$^+$ anticorrelation is still starless (Kirk et al. 2017) and the freeze-out timescales of molecules are long enough to differentiate the gas-phase abundance of CO and N$_2$. As a result, the N$_2$H$^+$ abundance increases after CO, which is the main destructor of N$_2$H$^+$, disappears. SM1 is located at the eastern edge of the C$^{18}$O depletion zone. Although the C$^{18}$O abundance at the position of SM1 derived from the combined maps of the continuum and C$^{18}$O, 1.9 × 10$^{-7}$, is not very low as compared to the interstellar value of (1.7–4.8) × 10$^{-7}$, this is because of the spatially extended emission along the line of sight. The C$^{18}$O abundance at SM1 is a factor of 20 lower if it is derived from the SMA data. This suggests that the CO depletion is also significant in the dense gas envelope of SM1. The C$^{18}$O abundance shows the lowest value of 4.3 × 10$^{-8}$ toward VLA 1623. Although the C$^{18}$O line traces the rotating disk around VLA 1623A, there is no C$^{18}$O emission from VLA 1623B and the envelope surrounding this binary system (Murillo & Lai 2013; Murillo et al. 2013). This implies that most of the dense gas surrounding the VLA 1623A/B binary system is colder than the CO freeze-out temperature. Interestingly, the N$_2$H$^+$ also shows the lowest abundance at VLA 1623. This implies that the temperature of the dense gas surrounding VLA 1623 is lower than the freeze-out temperature of N$_2$. Once both CO and N$_2$ freeze out completely, the N$_2$H$^+$ abundance does not increase when the gas is heated by the newly born star. Since the desorption energy of N$_2$ does not differ significantly from that of CO, the N$_2$ desorption area is expected to be comparable to the CO desorption area. In such a case, N$_2$H$^+$ is easily destructed by the CO desorbed from grains and cannot have enough abundance to be observed.

Molecular clouds irradiated externally by nearby stars are often found in high-mass star-forming regions. For example, molecular gas in the S255-S257 system is located between two HII regions, S255 and S257, and forms an elongated ridge compressed and illuminated by two HII regions (Minier et al. 2007). The dense gas ridge of this system harbors a cluster of YSOs with more than 100 members (Ojha et al. 2011). The morphology of the molecular ridge and the spatial distribution of the YSOs suggest that the star formation activity in this system is induced by the compression from two HII regions. On the other hand, the dense molecular ridge irradiated by two early-type stars on both sides is barely seen in the low-mass star-forming regions; ρ-Oph A is almost a unique example. In the case of ρ-Oph A, the effect of external sources is moderate. Molecular gas is interacting with the photon-dominated region (PDR) around the nearest star S1. The HII region around this star has a diameter of ∼20″ (Andre et al. 1988), which is much smaller than the size of the PDR. The curved ridge morphology observed in the C$^{18}$O (3–2) follows the outer edge of the spherical shell of the PDR around S1 traced by H$_2$, [O I] (Larsson & Liseau 2017), and [C II] (Mookerjea et al. 2018), suggesting that the molecular ridge has been compressed by the PDR. However, our C$^{18}$O (2–1) data do not show the kinematical signature of external compression.

5. Conclusions

We have studied the physical and chemical conditions of the ρ-Oph A region using the 1.3 mm continuum and molecular lines such as C$^{18}$O (2–1) and N$_2$H$^+$ (1–0). The 1.3 mm continuum and C$^{18}$O (2–1) data observed with the SMA were combined with the data obtained with the IRAM 30 m telescope.

![Figure 12. Three mm continuum map obtained by combining two ALMA data sets. The 1σ rms noise level is 0.18 mJy beam$^{-1}$. The green ellipse in the lower left corner denotes the synthesized beam size of 1″ × 1″.](image)
and JCMT, respectively, in order to fill the short-spacing information. Our main conclusions are summarized as follows:

1. The combined 1.3 mm map reveals that the three major sources, VLA 1623, SM1, and SM1N, are embedded in the extended emission running along the north–south direction. VLA 1623 and SM1 contain the spatially compact components, while SM1N does not have a compact component. The continuum emission around the SM1 peak is extended toward the northwest direction. The secondary peak, SM1-W, to the west of the SM1 peak implies the presence of small-scale clumps. However, the location of SM1-W does not coincide with those of the clumps reported in Nakamura et al. (2012).

2. In addition to VLA 1623 and SM1, two compact condensations, VLA 1623-N1 and VLA 1623-N2, are identified in the continuum ridge connecting VLA 1623 and SM1. In addition, VLA 1623-W is also identified as a separate peak. All of the small condensations identified in the ρ-Oph A region are gravitationally bounded. Among the newly discovered small condensations, VLA 1623-N1 has an X-ray counterpart and is likely to harbor a young stellar object. On the other hand, VLA 1623-N2 and SM1-W are starless.

3. The spatial distribution of the C$^{18}$O is significantly different from that of the continuum; the C$^{18}$O emission is enhanced at the eastern and western edges of the continuum ridge. The brightness temperature of the C$^{18}$O line is enhanced to 40–50 K in the eastern and western edges. This is consistent with the picture that the gas in the ρ-Oph A ridge is heated externally by the nearby B stars Oph S1 and HD 147889.

4. On the other hand, the gas in the inner dense ridge remains cold. The C$^{18}$O intensity drops below 15 K in the region between SM1 and SM1N. In this region, the C$^{18}$O abundance decreases and shows clear anticorrelation with the NH$_3$ abundance.

5. Both C$^{18}$O and NH$_3$ abundances decrease significantly toward the Class 0 protostar VLA 1623. This implies that most of the dense gas surrounding VLA 1623 is colder than the freeze-out temperature of N$_2$, which is a few degrees lower than that of CO.

6. The velocity structure of C$^{18}$O suggests that the ρ-oph A ridge consists of three components with different systemic velocities. These three velocity components are known to have different chemical properties: the northern component at 3.1 km s$^{-1}$ is deficient in deuterated species, the southern component at 3.7 km s$^{-1}$ is rich in deuterated species, and the northwestern component at 2.9 km s$^{-1}$ shows high abundance in methanol (Garay et al. 2002; Bergman et al. 2011).

7. The CH$_3$OH shows the blueshifted and redshifted components in the vicinity of SM1. These components are likely to trace the outflow activity of the embedded protostar in SM1. The similar components are also seen in the H$_2$CO. However, the spatially extended H$_2$CO emission does not show clear bipolarity.

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Facilities: SMA, IRAM:30 m, JCMT, ALMA.

Software: MIR (https://github.com/qi-molecules/sma-mir), MIRIAD (Sault et al. 1996), Astropy (The Astropy Collaboration 2013, 2018), Starlink (Currie et al. 2014), CASA (Mcmullin et al. 2007).

Appendix

The 3 mm ALMA Continuum Map of the ρ-oph A Ridge

In Figure 12, we present the 3 mm continuum map of the ρ-oph A ridge, which is made by combining ALMA data from two projects (Project code = 2013.1.00187.S and 2016.1.01468.S). The ALMA data sets were obtained from the ALMA Science Archive. The first Band 3 observations from project 2013.1.00187.S were made during cycle 2 on 2015 January 31. The array consisted of 37 antennas with relatively compact configuration. The field center is at the position of VLA 1623. The continuum data were obtained at 101, 103, and 113 GHz, each covering a bandwidth of 2 GHz. The total integration time is 60.48 s. The details of the observation are also described in Kirk et al. (2017).

The second Band 3 observations from project 2016.1.01468.S were made during cycle 4 on 2016 November 16. The array was in C40-4 configuration. The field is also centered at the position of VLA 1623. The observation covers a frequency range from 108.72 to 110.94 GHz. The total integration time is 241.92 s.

CASA (Mcmullin et al. 2007) was used to calibrate and reduce both data sets. We concatenated two calibrated data sets and used “tclean” in the mfs (multifrequency synthesis) mode to generate the combined 3 mm continuum map. The robust weighting of 0.5 was adopted, providing the synthesized beam size of $1.7' \times 1.7'$. The rms noise level of the 3 mm continuum image is 0.18 mJy beam$^{-1}$.

ORCID iDs
Yu-Ching Chen © https://orcid.org/0000-0002-9932-1298
Naomi Hirano © https://orcid.org/0000-0001-9304-7884

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