Methanol and its Relation to the Water Snowline in the Disk around the Young Outbursting Star V883 Ori

Merel L. R. van 't Hoff1, John J. Tobin1,2, Leon Trapman1, Daniel Harsono1, Patrick D. Sheehan2, William J. Fischer3, S. Thomas Megeath4, and Ewine F. van Dishoeck1,5

1 Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands; vthoff@strw.leidenuniv.nl
2 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, 440 West Brooks Street, Norman, OK 73019, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
4 Ritter Astrophysical Research Center, Department of Physics and Astronomy, University of Toledo, 2801 West Bancroft Street, Toledo, OH 43606, USA
5 Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany

Received 2018 July 17; revised 2018 August 15; accepted 2018 August 18; published 2018 August 31

Abstract

We report the detection of methanol in the disk around the young outbursting star V883 Ori with the Atacama Large Millimeter/submillimeter Array. Four transitions are observed with upper-level energies ranging between 115 and 459 K. The emission is spatially resolved with the 0.14 arcmin beam and follows the Keplerian rotation previously observed for C18O. Using a rotational diagram analysis, we find a disk-averaged column density of \( \sim 10^{17} \) cm\(^{-2}\) and a rotational temperature of \( \sim 90-100 \) K, suggesting that the methanol has thermally desorbed from the dust grains. We derive outer radii between 120 and 140 au for the different transitions, compared to the 360 au outer radius for C18O. Depending on the exact physical structure of the disk, the methanol emission could originate in the surface layers beyond the water snowline. Alternatively, the bulk of the methanol emission originates inside the water snowline, which can then be as far out as \( \sim 100 \) au, instead of 42 au as was previously inferred from the continuum opacity. In addition, these results show that outbursting young stars like V883 Ori are good sources to study the ice composition of planet-forming material through thermally desorbed complex molecules, which have proven to be hard to observe in more evolved protoplanetary disks.

Key words: circumstellar matter – ISM: molecules – stars: individual (V883 Ori) – stars: pre-main sequence

1. Introduction

Snowlines in disks around young stars mark the midplane locations where molecular species freeze out from the gas phase onto dust grains. The most important snowline for planet formation is the water snowline. Planetesimal formation is expected to be significantly enhanced at this snowline because the bulk of the ice mass is in water ice (e.g., Stevenson & Lunine 1988; Ros & Johansen 2013; Schoonenberg & Ormel 2017). In addition, the elemental composition of the gas and ice changes across this snowline because water is a major carrier of oxygen. The bulk composition of planets therefore depends on their formation location with respect to the water snowline (e.g., Öberg et al. 2011; Madhusudhan et al. 2014; Eistrup et al. 2018).

For water, the transition from ice to gas occurs when the temperature exceeds roughly 100 K (Fraser et al. 2001). This places the snowline at a few au from the star in protoplanetary disks, making it hard to observe. However, heating is temporarily enhanced during protostellar accretion bursts, which causes ices to sublime out to larger radii. After such a burst, the circumstellar dust cools rapidly (Johnstone et al. 2013), while for the molecules it takes much longer to freeze back onto the grains (Rodgers & Charnley 2003). As a result, snowlines are shifted away from the star (Lee 2007; Visser & Bergin 2012; Vorobyov et al. 2013; Visser et al. 2015). This has been observed for CO toward a sample of protostars (Jørgensen et al. 2015; Frimann et al. 2017).

V883 Ori is an FU Orionis object in the Orion A L1641 molecular cloud (\( d \sim 400 \) pc; Kounkel et al. 2017) with a bolometric luminosity of \( \sim 218 \) L\(^\odot\) (Strom & Strom 1993; Furlan et al. 2016). Although the onset of the V883 Ori outburst was not directly observed, evidence for an ongoing outburst that began before 1888 comes from its associated reflection nebula (Pickering 1890) and the similarity of its near-infrared (near-IR) spectrum to that of FU Ori (Connelley & Reipurth 2018). The 1.3 M\(^\odot\) star is surrounded by a \( \geq 0.3 \) M\(^\odot\) rotationally supported disk (Cieza et al. 2016, 2018) still embedded in its envelope.

The location of the water snowline in V883 Ori was inferred from a change in the continuum opacity at 42 au (Cieza et al. 2016), which may be due to a pileup of dust interior to the snowline (Birnstiel et al. 2010; Banzatti et al. 2015; Pinilla et al. 2016), or water evaporation and re-coagulation of silicates (Schoonenberg et al. 2017). However, the origin of various structures seen in continuum emission of disks is still heavily debated and radial discontinuities in the spectral index are not necessarily related to snowlines (van Terwisga et al. 2018). Molecular observations are thus needed to confirm or refute the snowline location. Unfortunately, water is hard to observe from the ground and warm water (\( T \gtrsim 100 \) K) has not yet been observed in young disks (D. Harsono et al. 2018, in preparation), so observing the snowline directly is difficult. A complementary approach is to observe other molecules whose distribution can be related to the snowline. Methanol (CH\(_3\)OH) is generally used to probe the \( \gtrsim 100 \) K region in hot cores (Herbst & van Dishoeck 2009), because its volatility is similar to that of water (e.g., Brown & Bolina 2007).

We serendipitously detected spatially resolved methanol emission in the V883 Ori disk with the Very Large Array/Atacama Large Millimeter/submillimeter Array (VLA/ALMA) Nascent Disk And Multiplicity Orion survey that aims to characterize the embedded disks in Orion (PI: Tobin, J. J. Tobin et al. 2018, in preparation). Analysis of the methanol observations and comparison with earlier C18O observations...
shows that the methanol is thermally desorbed and suggests that the water snowline can be as far out as \(~\sim 100\) au.

2. Observations

V883 Ori was observed on 2016 September 6 and 2017 July 19 in Band 7 as part of ALMA Cycle 4 project 2015.1.00041.S. The total on-source integration time was 54 s, and baselines between 16.7 and 3697 m were covered. The correlator setup consisted of two low spectral resolution (31.25 MHz) 1.875 GHz continuum windows centered at 333 and 344 GHz, a 234.375 MHz spectral window (122 kHz resolution) centered at 330.6 GHz, and a 937.5 MHz spectral window (488 kHz \(~\sim 0.42\) km s\(^{-1}\) resolution) centered at 345.8 GHz. The latter spectral window contained the methanol transitions. The bandpass calibrator was J0510+1800 for the 2016 observations and J0522-3627 for the 2017 observations. The absolute flux calibrators were J0510+1800, J0522-3627, and J0750+1231 for the respective executions, and J0541-0541 was used as complex gain calibrator for all executions. The data were reduced manually by the Dutch Allegro ARC Node to properly account for variation of quasar J0510+1800. Following the standard calibration, phase-only self-calibration was performed on the continuum data using version 4.7.2 of the Common Astronomy Software Application (CAS: McMullin et al. 2007). The self-calibration solutions were also applied to the spectral line data. The line data was imaged after continuum subtraction, using the CASA task clean with natural weighting and a velocity resolution of 0.5 km s\(^{-1}\). This resulted in a synthesized beam size of \(0''13 \times 0''14\) and an rms of 21 mJy beam\(^{-1}\) per channel.

V883 Ori was also observed in Band 6 (project 2013.1.00710.S). In these observations the correlator was configured to have one baseline centered on the \(^{13}\)CO \(J=2\rightarrow1\) transition at 219.560 GHz. The \(^{13}\)CO data reduction is described by Cieza et al. (2016). The resulting image has a synthesized beam of \(0''23 \times 0''30\) and an rms of 9 mJy beam\(^{-1}\) in 0.5 km s\(^{-1}\) channels.

3. Results

3.1. Detection of Warm Methanol in the Disk

The spectral setting of the ALMA Band 7 observations covers four CH\(_3\)OH lines with upper-level energies ranging from 115 to 459 K (see Table 1). Spectra centered at the corresponding rest frequencies are presented in Figure 1. All four lines are detected between \(~\sim 0.5\) and \(~\sim 7.0\) km s\(^{-1}\), but the two nearby \(5_{4}\rightarrow6_{3}\) transitions from \(A^+\) and \(A^-\) CH\(_3\)OH are blended. The peak signal-to-noise in the 0.5 km s\(^{-1}\) channels is \(~4\) for the highest energy transition (18\(_{3}\)→17\(_{4}\)) and \(~5\) for the other lines.

In addition to the CH\(_3\)OH transitions, several other lines are marginally detected (Figure 1, top panels). Using the Jet Propulsion Laboratory (Pickett et al. 1998) and the Cologne Database for Molecular Spectroscopy (Müller et al. 2001) databases through Splatalogue,\(^6\) we can assign transitions of \(^{15}\)CH\(_3\)OH, the formaldehyde isotopologues H\(_2\)C\(^{15}\)O and D\(_2\)CO, methyl formate (CH\(_3\)OCHO), and acetaldehyde (CH\(_3\)CHO). The peak signal-to-noise of these transitions are \(~4\)–\(~5\)σ in 1.0 km s\(^{-1}\) channels, but unambiguous identification requires detection of more lines.

The CH\(_3\)OH channel maps (not shown) display the the same butterfly pattern as \(^{18}\)O\(_3\), typical for a Keplerian rotating disk (Cieza et al. 2016). The kinematics can be more clearly visualized using moment maps. Figure 2 (top panels) shows the moment-zero (integrated intensity) maps for blueshifted and redshifted emission of the different CH\(_3\)OH transitions overlaid the same moment zero map as \(^{13}\)CO, typical for a Keplerian rotating disk. The CH\(_3\)OH emission is more compact than the \(^{13}\)CO emission, but for all CH\(_3\)OH transitions a similar velocity gradient is observed with the blueshifted part of the CH\(_3\)OH disk and not in the surrounding envelope or outflow.

3.2. Column Density and Excitation Temperature

A rotational diagram for CH\(_3\)OH is presented in Figure 3. The total flux for the two \(5_{4}\rightarrow6_{3}\) transitions is divided by two, because the two lines have the same upper-level energy and Einstein A coefficient. Fitting a linear function results in a rotation temperature of 104 ± 8 K when the flux is extracted within a 0''6 aperture, and \(T_{\text{rot}} = 92 \pm 6\) K for the Keplerian mask with an outer radius of 225 au (0''54). The resulting disk-averaged column densities are \((8.9 \pm 1.6) \times 10^{16}\) cm\(^{-2}\) and \((1.4 \pm 0.2) \times 10^{17}\) cm\(^{-2}\), respectively.

If the emission is optically thin and in local thermodynamic equilibrium (LTE), the rotational temperature equals the kinetic temperature of the gas. For densities higher than

\(^6\) http://www.splatalogue.net
$10^8$–$10^9$ cm$^{-3}$ the CH$_3$OH excitation temperature is similar to the kinetic temperature (see e.g., Johnstone et al. 2003; Jørgensen et al. 2016), so LTE is a valid assumption in the bulk of the disk where the density is of order $10^3$–$10^{13}$ cm$^{-3}$. The observed ratios of the integrated fluxes are consistent with optically thin emission based on an LTE calculation, although optically thick emission cannot be completely ruled out with the signal-to-noise of the observations. However, upper levels with an energy of 459 K are hardly populated at temperatures $\gtrsim$75 K, so LTE is a valid assumption in the bulk of the disk where the density is of order $10^3$–$10^{13}$ cm$^{-3}$. The same elliptical apertures are used as for the radial intensity profiles. The resulting outer radii are listed in Table 1 and indicated in Figure 2 (bottom panels). The CH$_3$OH outer radii range between $\sim$117 and $\sim$142 au for the different transitions, with the outer radius decreasing with upper-level energy. The CH$_3$OH outer radii are $\sim$2.5–3.0× smaller than the C$^{18}$O outer radius of $\sim$361 au. The largest angular scale is $\sim$4$''$ ($\sim$1650 au) for the C$^{18}$O observations and $\sim$1$''$5 ($\sim$600 au) for the CH$_3$OH observations.

4. Discussion

4.1. Location of the Water Snowline

The distribution of CH$_3$OH, and hence the relationship between its emission and the water snowline, depends on the physical structure of the disk, as illustrated in Figure 4. CH$_3$OH is present in the gas phase where the temperature exceeds the
thermal desorption temperature of \( \sim 100 \) K, and where there is a sufficiently large column of material to shield the ultraviolet (UV) radiation and prevent photodissociation (\( A_V > 3 \)). In the surface layers, the photodissociation timescale is tens of years (Heays et al. 2017), comparable to the outburst duration (10–100 years). This means that the radial extent of the methanol layer higher up in the disk beyond the midplane water snowline is set by the intercept of the snow surface and the \( A_V = 3 \) contour. In addition, the magnitude of the CH\(_3\)OH column density drop across the water snowline depends on the height of the snow surface; the higher up in the disk, the larger the drop. Whether the emission then traces this column density profile depends on the optical depth of both the CH\(_3\)OH and the dust.

Due to this interplay of several parameters, a detailed physical model of the disk is required to derive the water snowline location from methanol emission. It may thus be possible to see CH\(_3\)OH emission out to \( \sim 120–140 \) au, while the snowline is around 40 au. This would require, for example, a water snow surface close to the midplane, and/or optically thick methanol emission (Facchini et al. 2017). However, especially if the emission is optically thin, the bulk of the methanol emission is more likely to originate inside the water snowline (Figure 4, right panel), as the CH\(_3\)OH column density can drop \( \sim 3 \) orders of magnitude crossing the snowline, assuming a constant abundance for the
gas-phase CH$_3$OH (see e.g., the simple model for the CO snowline in Qi et al. 2013). Assuming a step function for the column density, this would mean that the snowline in V883 Ori can be as far out as $\sim$100–125 au, taking into account the 40 au beam by deconvolving the radial profiles.

Non-thermal desorption processes are not expected to influence the relationship between CH$_3$OH and the water snowline. Such processes have been invoked to explain the CH$_3$OH emission in TW Hya (Walsh et al. 2016), but this required gas-phase CH$_3$OH outside of the CO snowline ($T \lesssim 20$ K) at an abundance of $\sim$10$^{-12}$–10$^{-11}$, several orders of magnitude lower than observed here and expected from ice abundances (Section 3.2).

In addition to detailed modeling, observations of other molecular tracers could put better constraints on the water snowline location. H$^13$CO$^+$ has proven to be a promising tracer in the envelope around NGC 1333 IRAS2A (van Hoff et al. 2018), because the main destroyer of HCO$^+$ is gas-phase water.

4.2. Ice Composition of Planet-forming Material

One of the key questions in planet formation is whether planetary systems inherit their chemical composition from the natal cloud, or whether the material is significantly processed en route to the disk. Observations of many complex molecules, including methanol, around young protostars at solar system scales (e.g., Jørgensen et al. 2016) and in comets (e.g., Mumma & Charnley 2011; Le Roy et al. 2015) show that a large complexity is present during both the early as well as the final stages of planet formation. The chemical complexity in protoplanetary disks, however, is hard to probe. Due to the low temperatures (<100 K), complex molecules are frozen out onto dust grains at radii larger than a few au, and ices can only be observed through infrared absorption in edge-on systems.

Although alternative desorption processes may get these molecules into the gas phase, as has been shown for water (Hogerheijde et al. 2011), so far only CH$_3$OH and CH$_3$CN have been observed in disks (Öberg et al. 2015; Walsh et al. 2016; Bergner et al. 2018; Loomis et al. 2018). Moreover, as it is unclear what processes operate for each species and what the efficiencies are, the observed gas composition cannot directly be linked to the ice composition of planet-forming bodies.

The results presented here show that complex molecules can thermally desorb in disks around young stars that have recently undergone an accretion burst. Moreover, their emission extends out to more than 100 au around V883 Ori and is readily detected and spatially resolved with only one minute of integration with ALMA. V883 Ori is the longest-lasting known outburst and one of, if not the, most luminous. This makes it an archetype for understanding disk chemistry in fainter outbursts. It also provides a look at how younger outbursts may evolve over the century following their outbursts. Young disks like V883 Ori thus provide the unique opportunity to study the chemical complexity at the onset of planet formation.

We thank the referee for helpful comments. Astrochemistry in Leiden is supported by NOVA, KNAW and EU A-ERC grant 291141 CHEMPLAN. M.L.R.H. acknowledges support from a Huygens fellowship from Leiden University. J.J.T. acknowledges support from the Homer L. Dodge Endowed Chair at the University of Oklahoma and NWO grant 639.041.439. This Letter makes use of the following ALMA data: ADS/JAO.ALMA##2013.1.00710.S, and ADS/JAO.ALMA##2015.1.00350.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with
the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

**ORCID iDs**

Merel L. R. van ’t Hoff @ https://orcid.org/0000-0002-2555-9869

John J. Tobin @ https://orcid.org/0000-0002-6195-0152

Patrick D. Sheehan @ https://orcid.org/0000-0002-3747-2496

S. Thomas Megeath @ https://orcid.org/0000-0001-7629-3573

Ewine F. van Dishoeck @ https://orcid.org/0000-0001-7591-1907

**References**

Ansdell, M., Williams, J. P., Trapman, L., et al. 2018, ApJ, 859, 21

Banzatti, A., Pinilla, P., Ricci, L., et al. 2015, ApJL, 815, L15

Bergner, J. B., Guzmán, V. G., Öberg, K. I., Loomis, R. A., & Pegues, J. 2018, ApJ, 857, 69

Birnstiel, T., Dullemond, C. P., & Brauer, F. 2010, A&A, 513, A79

Boogert, A. A. C., Gerakines, P. A., & Whittet, D. C. B. 2015, ARA&A, 53, 541

Brown, W. A., & Bolina, A. S. 2007, MNRAS, 374, 1006

Cieza, L. A., Casassus, S., Tobin, J., et al. 2016, Natur, 535, 258

Cieza, L. A., Ruiz-Rodriguez, D., Perez, S., et al. 2018, MNRAS, 474, 4347

Connelley, M., & Reipurth, B. 2018, ApJ, 861, 145

Eistrup, C., Walsh, C., & van Dishoeck, E. F. 2018, A&A, 613, A14

Facchini, S., Birnstiel, T., Bruderer, S., & van Dishoeck, E. F. 2017, A&A, 605, A16

Fraser, H. J., Collings, M. P., McCoustra, M. R. S., & Williams, D. A. 2001, MNRAS, 327, 1165

Frinman, S., Jørgensen, J. K., Dunham, M. M., et al. 2017, A&A, 602, A120

Furlan, E., Fischer, W. J., Ali, B., et al. 2016, ApJS, 224, 5

Heays, A. N., Bosman, A. D., & van Dishoeck, E. F. 2017, A&A, 602, A105

Herbst, E., & van Dishoeck, E. F. 2009, ARA&A, 47, 427

Hogerheijde, M. R., Bergin, E. A., Brinch, C., et al. 2011, Sci, 334, 338

Johnstone, D., Boonman, A. M. S., & van Dishoeck, E. F. 2003, A&A, 412, 157

Johnstone, D., Hendricks, B., Herczeg, G. J., & Bruderer, S. 2013, ApJ, 765, 133

Jørgensen, J. K., van der Wiel, M. H. D., Coutens, A., et al. 2016, A&A, 595, A117

Jørgensen, J. K., Visser, R., Williams, J. P., & Bergin, E. A. 2015, A&A, 579, A23

Kounkel, M., Hartmann, L., Loinard, L., et al. 2017, ApJ, 834, 142

Le Roy, L., Altweck, K., Balisiger, H., et al. 2015, ApJL, 794, L12

Lee, J.-E. 2007, JAS, 40, 83

Loomis, R. A., Cleeves, L. I., Öberg, K. I., et al. 2018, ApJ, 859, 131

Madhusudhan, N., Amin, M. A., & Kennedy, G. M. 2014, ApJL, 794, L12

McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, P. Hill, & D. J. Bell (San Francisco, CA: ASP), 127

Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, A&A, 370, L49

Mumma, M. J., & Charnley, S. B. 2011, ARA&A, 49, 471

Öberg, K. I., Guzmán, V. V., Furuya, K., et al. 2015, Natur, 520, 198

Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJL, 743, L16

Pickering, E. C. 1890, AnHar, 18, 113

Pickett, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, JQSRT, 60, 883

Pinilla, P., Klarmann, L., Birnstiel, T., et al. 2016, A&A, 585, A35

Qi, C., Öberg, K. I., Wilner, D. J., et al. 2013, Sci, 341, 630

Rodgers, S. D., & Charnley, S. B. 2003, ApJ, 585, 355

Ros, K., & Johansen, A. 2013, A&A, 552, A137

Salinas, V. N., Hogerheijde, M. R., Mathews, G. S., et al. 2017, A&A, 606, A123

Schoonenberg, D., Okuzumi, S., & Ormel, C. W. 2017, A&A, 605, L2

Schoonenberg, D., & Ormel, C. W. 2017, A&A, 602, A21

Stevenson, D. J., & Lunine, J. I. 1988, Icar, 75, 146

Strom, K. M., & Strom, S. E. 1993, ApJL, 412, L63

Tripathi, A., Andrews, S. M., Birnstiel, T., & Wilner, D. J. 2017, ApJ, 845, 44

van Terwisga, S. E., van Dishoeck, E. F., Ansdell, M., et al. 2018, A&A, 616, A89

van ’t Hoff, M. L. R., Persson, M. V., Harsono, D., et al. 2018, A&A, 613, A29

Visser, R., & Bergin, E. A. 2012, ApJL, 754, L18

Visser, R., Bergin, E. A., & Jørgensen, J. K. 2015, A&A, 577, A102

Vorobyov, E. I., Baraffe, I., Harries, T., & Chabrier, G. 2013, A&A, 557, A35

Walsh, C., Loomis, R. A., Öberg, K. I., et al. 2016, ApJL, 823, L10

Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191