The Circumstellar Environment around the Embedded Protostar EC 53

Seokho Lee1,6, Jeong-Eun Lee1, Yuri Aikawa2, Gregory Herczeg3, and Doug Johnstone4,5

1 School of Space Research, Kyung Hee University, 1732 Deogyo-geun-daero, Giheung-gu, Yongin-si, Gyeonggi-do, Republic of Korea; seokho.lee@nao.ac.jp, jjeonglee@ku.ac.kr
2 Department of Astronomy, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
3 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China
4 NRC Herzberg Astronomy and Astrophysics, 5071 West Saanich Road, Victoria, BC, V9E 2E7, Canada
5 Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 5C2, Canada

Received 2019 September 24; revised 2019 November 16; accepted 2019 November 18; published 2020 January 21

Abstract

EC 53 is an embedded protostar with quasi-periodic emission in the near-IR and submillimeter. We use Atacama Large Millimeter/submillimeter Array (ALMA) high-resolution observations of continuum and molecular line emission to describe the circumstellar environment of EC 53. The continuum image reveals a disk with a flux that suggests a mass of 0.075 $M_\odot$, much less than the estimated mass in the envelope, and an in-band spectral index that indicates grain growth to centimeter sizes. Molecular lines trace the outflow cavity walls, infalling and rotating envelope, and/or the Keplerian disk. The rotation profile of the C$^{18}$O 3–2 line emission cannot isolate the Keplerian motion clearly, although the lower limit of the protostellar mass can be calculated as $0.3 \pm 0.1 M_\odot$ if the Keplerian motion is adopted. The weak CH$_3$OH emission, which is anticorrelated with the H$^{13}$CO$^+$ 4–3 line emission, indicates that the water snow line is more extended than what expected from the current luminosity, attesting to bygone outburst events. The extended snow line may persist for longer at the disk surface because the lower density increases the freeze-out timescale of methanol and water.

Unified Astronomy Thesaurus concepts: Protostars (1302); Protoplanetary disks (1300); Spectral index (1553); Interstellar molecules (849)

1. Introduction

Low-mass protostars form through the gravitational collapse of molecular cloud cores. The core material accretes onto protostars through a temporal reservoir, the accretion disk. Historical star formation models with a constant accretion rate of a few $10^{-6} M_\odot$ yr$^{-1}$ (e.g., Shu 1977; Masunaga & Inutsuka 2000) predict protostellar luminosities that are much higher than the actual luminosities of most protostars (e.g., Kenyon et al. 1990; Enoch et al. 2009; Dunham et al. 2010). One promising solution of this luminosity problem is the episodic accretion, although other time-dependent solutions are also possible (see the discussion of Hartmann et al. 2016 and Fischer et al. 2017).

Several observational phenomena support the episodic accretion directly or indirectly. Bursts in the optical brightness with various timescales are observed in FU Orionis objects (e.g., Herbig 1977, 2008; Audard et al. 2014) and EXors (e.g., Aspin & Reipurth 2000; Köpjd et al. 2008; Lorenzetti et al. 2012). Knots along jets and clumpy structures in protostellar outflows (e.g., Plunkett et al. 2015) could be also induced by accretion variability. In addition, the variation in accretion luminosity affects the chemistry in the disk and envelope (e.g., Lee 2007; Visser et al. 2015); the 15.2 $\mu$m pure CO$_2$ ice absorption features toward low-luminosity protostars (Kim et al. 2012) and the extended snow lines of volatiles compared with the theoretical snow line locations expected from the current luminosity (Jørgensen et al. 2013, 2015) are explained by past bursts of accretion. Brightness variation in the submillimeter by the accretion burst is detectable even for embedded protostars (Johnstone et al. 2013), as demonstrated for the Class 0 star HOPS 383 and two massive protostars (Safron et al. 2015; Hunter et al. 2017; Liu et al. 2018).

Although the mechanism of episodic accretion in protostars has not yet been securely identified, two main ideas are proposed to explain the large accretion bursts. First, disk instabilities, such as thermal instability (Bell & Lin 1994), gravitational instability (e.g., Vorobyov & Basu 2010), and the combined effect of both magnetorotational instability and gravitational instability (Zhu et al. 2009; Bae et al. 2014), may trigger a large amount of mass to accrete through the disk and onto the star. The other type of possible mechanism is the perturbation of the disk by an external trigger, such as a binary companion (Bonnell & Bastian 1992), the tidal disruption of radially migrating gas clumps/giant planets (Vorobyov & Basu 2005; Nayakshin & Lodato 2012), or disk variability linked to a stellar magnetic cycle (Armitage 1995; D’Angelo & Spruit 2012; Armitage 2016). The role of these mechanisms may be more important at earlier stages in protostellar growth, however any evolutionary change is difficult to evaluate with most surveys, as the common optical and near-IR survey probe later stages in the evolution of young stellar objects (e.g., Hillenbrand & Frideisen 2015; Contreras et al. 2017, 2019).

Recently, the JCMT-Transient monitoring survey has been searching for variability at the protostellar stage with monthly monitoring of submillimeter continuum emission in eight nearby star-forming regions (Herczeg et al. 2017). The first submillimeter variable detected in this survey, EC 53 (Yoo et al. 2017), stands out in amplitude relative to other protostars in the eight fields (Mairs et al. 2017; Johnstone et al. 2018). EC 53, first identified by Eiroa & Casali (1992) as a member of the Serpens Main Cloud (distance of 436 ± 9 pc Ortíz-León et al. 2017), is an embedded protostar with a bolometric luminosity of 1.7–4.8 $L_\odot$ (Enoch et al. 2009; Evans et al. 2009; Gutermuth et al. 2009; Dionatos et al. 2010; Dunham et al. 2015). Past near-IR monitoring shows that the K magnitude of EC 53 varies with a period of ~543 days (Hodapp 1999; Hodapp et al. 2012). The
submillimeter observations (Yoo et al. 2017) confirm this periodicity and strongly suggests that this submillimeter variability should be induced by the variable accretion rate. In addition, this short ∼1.5 yr variability may be related with a very close companion or a protoplanet, which can induce the periodic gravitational instability in the disk (Lodato & Clarke 2004). This short-period brightness variation of an embedded protostar in submillimeter casts an important question on when planets start to form.

The range of instabilities and the consequences of outbursts are both expected to leave traces in the circumstellar environment in the immediate vicinity of the protostar. To better describe the kinematics and chemical properties of this environment, we have obtained high-resolution ALMA imaging of gas and dust.

2. Observations

The observation of EC 53 was carried out with ALMA during Cycle 4 (2016.1.01304.T, PI: Jeong-Eun Lee) on 2017 May 21. The four spectral windows were set for 336.995–337.229 GHz, 338.345–338.579 GHz, 346.945–347.180 GHz, and 349.396–349.630 GHz, each with a spectral resolution of 244.141 kHz (∼0.2 km s$^{-1}$). This setup contains C$^{17}$O 3–2, CH$_3$OH 7$K_2$, 7$K_1$, H$^{13}$CO$^+$ 4–3, CCH $N = 4–3$, $J = 7/2–5/2$, $F = 4–3$, and $F = 3–2$ lines. Forty-one 12 m antennas were used in the C40-5 configuration, with baselines in the range from 15.1 m to 1.1 km. The total observing time on EC 53 was 48.1 minutes.

The data were initially calibrated using the CASA 4.7.2 pipeline (McMullin et al. 2007). The quasar J1751+0939 was used as a bandpass and amplitude calibrator, and the nearby quasar J1830+0619 was used as a phase calibrator. Self-calibration was applied for better imaging.

For molecular lines, natural weighting with a UV taper of 0$''$2 was used to obtain images with a higher signal-to-noise ratio (S/N) and a resolution of 0$''$3. A spectral resolution of 0.25 km s$^{-1}$ was used for strong C$^{17}$O, H$^{13}$CO$^+$, and CCH lines, while 0.5 km s$^{-1}$ was used for weak lines to reduce the rms noise. Table 1. The rms noise level for the strong molecular lines is ∼4 mJy beam$^{-1}$ near the continuum peak. The images of C$^{17}$O, H$^{13}$CO$^+$, and two strong CCH lines were produced by Briggs weighting with a robust factor of 0.5 to obtain higher resolution (0$''$2).

A dust continuum image was produced using line-free channels and was cleaned with two weightings: (1) natural weighting with the UV taper of 0$''$2 to compare with the molecular line images and (2) uniform weighting only with the UV distances longer than 500 k$\lambda$ to obtain a higher spatial resolution, with a beam size of 0$''$15 × 0$''$11 oriented at position angle of −88.4$^\circ$. The rms noise levels of the two images are 0.21 and 0.38 mJy beam$^{-1}$, respectively. The data are analyzed in the image plane.

| Molecule | Frequency (GHz) | Transition | log$_{10}$$A^\lambda$ (s$^{-1}$) | $E_{cm}$ (K) | $k_{cm}$ |
|----------|----------------|------------|-----------------|-------------|----------|
| C$^{17}$O | 337.060988$^d$ | $J = 3$–2 | −5.63433 | 32.4 | 12 |
| C$^{13}$S | 337.396459 | $J = 7$–6 | −3.1804 | 50.2 | 15 |
| CH$_3$OH | 338.346280$^e$ | $7(−1, 1)−6(−1, 0)$ | −3.37817 | 70.5 | 15 |
| | 338.4086810$^e$ | $7(0, 7)−6(0, 6)$ | −3.76902 | 65.0 | 15 |
| | 338.7216300$^e$ | $7(2, 6)−6(2, 5)$ | −3.80441 | 99.0 | 15 |
| | 338.7229400$^e$ | $7(−2, 6)−6(−2, 5)$ | −3.80441 | 99.0 | 15 |
| H$^{13}$CO$^+$ | 346.9983440 | $J = 4$–3 | −2.48309 | 41.6 | 9 |
| CCH | 349.3992756$^f$ | $N = 4–3$, $J = 7/2–5/2$, $F = 4–3$ | −3.90313 | 41.9 | 9 |
| | 349.4006712$^f$ | $N = 4–3$, $J = 7/2–5/2$, $F = 3–2$ | −3.92139 | 41.9 | 7 |
| | 349.4146425$^{g,e}$ | $N = 4–3$, $J = 7/2–5/2$, $F = 3–3$ | −5.15397 | 41.9 | 7 |
| | 349.6036139$^{g,e}$ | $N = 4–3$, $J = 7/2–7/2$, $F = 4–4$ | −5.28599 | 41.9 | 9 |

Notes. The molecular information is adopted from CDMS database (Müller et al. 2001).

$^a$ Einstein $A$-coefficient.
$^b$ Energy state of the upper level.
$^c$ Statistical weight of the upper level.
$^d$ Frequency of the strongest hyperfine line in C$^{17}$O 3–2.
$^e$ Marginally detected line.
$^f$ Strong CCH line.
$^g$ Weak CCH line.
3. Results

3.1. Dust Continuum Images

The 343.4 GHz (873 μm) continuum image with a lower resolution (Figure 1) shows extended emission along the north-south direction as well as a compact source. The compact source is resolved in the higher resolution image as shown on the left panel of Figure 2. The compact emission could originate from the disk (see Sections 3.2.1 and 4.1). The properties of the continuum emission are derived by fitting a Gaussian profile using the task “imfit” in CASA.

The peak of the continuum emission is located at \( \alpha(J2000) = 18^h29^m51^s17685 \) and \( \delta(J2000) = +01^d16^m40^s3892 \). This peak position is consistent to within \( \sim 0.3^\circ \) of the positions from Spitzer (Harvey et al. 2006; Hsieh & Lai 2013), VLA (Ortiz-León et al. 2015), and high-resolution Keck Ks-band imaging (Hodapp et al. 2012), after applying the proper motion correction for Serpens Main of \( \sim 10 \) mas yr\(^{-1} \) toward the southeast (Ortiz-León et al. 2017; Herczeg et al. 2019). The position is offset to the north of the 2MASS (Cutri et al. 2003) and neoWISE (Cutri et al. 2014) positions, likely a result of nebulosity seen to the south of the EC 53 binary system by Hodapp et al. (2012).

The deconvolved image of the disk shows that the major and minor axes are \( 144.2 \pm 2.4 \) mas and \( 118.4 \pm 2.2 \) mas with a position angle of \( 60.0 \pm 4.2^\circ \). The ratio of the major and minor axes suggests the disk inclination of \( 34.8 \pm 2.7^\circ \). When this position angle and the inclination are adopted, the disk radius that encircles 95\% of the disk flux is \( 214 \) mas (93 au at the distance of 436 pc), similar to the typical size of more evolved protoplanetary disks (e.g., Tripathi et al. 2017; Cieza et al. 2019; Long et al. 2019).

This position angle and inclination are both consistent with previous observations. The observed position angle of the disk is roughly perpendicular to the direction of the H2 jet at 140° (Herbst et al. 1997) and the \(^{12}\)CO 3–2 outflow at 135° (Dionatos et al. 2010). Hodapp et al. (2012) suggested that the disk of EC 53 is seen nearly edge-on based on the cometary feature in the near-IR image. However, the inclination of the outflow axis could be lower than the half-opening angle of the outflow cavity when a protostar is observed in near-IR scattered light (Reipurth et al. 2000). Indeed, the near-IR image of EC 53 (Figure 6 in Hodapp et al. 2012, see the blue dashed curve on the bottom right panel in Figure 3) indicates that the half-opening angle of the outflow cavity is smaller than 45° and the inclination is between 30° and 45° (see Figure 17 in Reipurth et al. 2000). The best-fit spectral energy distribution model of EC 53 also requires a small inclination of 30° (Baek et al. 2019).

Furthermore, for Class I sources, [Fe II] forbidden lines trace high velocity gas with a radial velocity of 100–200 km s\(^{-1}\) (Davis et al. 2011). Near-IR spectra of EC 53 show that the 1.644 μm [Fe II] line is blueshifted by \( \sim 170 \) km s\(^{-1}\) (S. Park et al. 2019, in preparation), which implies that the inclination of the jet should be close to face-on.

The peak intensity and total flux of the disk, which are measuring by applying “imfit” to the left image of Figure 2, are 69.3 ± 0.4 mJy beam\(^{-1}\) and 139.7 ± 1.2 mJy, respectively. The compact emission shown in the lower resolution image (Figure 1) has the flux of 155 mJy within an aperture of 0.7, implying that the compact emission is mostly radiated from the disk shown in the high-resolution image (Figure 2). On the other hand, the total continuum flux in Figure 1 is 330 mJy. The 850 μm flux (in the beam of 14″6) of EC 53 with the JCMT/SCUBA-2 is 960 mJy at the quiescent phase (Yoo et al. 2017), and thus, at least 60\% of the continuum emission arises from an extended envelope and is resolved out in this ALMA observation.

The disk mass may be estimated from the continuum flux by

\[
M_{\text{disk}} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\text{dust}})},
\]

where \( F_\nu \) is the observed flux (139.7 ± 1.2 mJy), \( d \) is the distance to EC 53, \( \kappa_\nu \) is the dust opacity, and \( B_\nu(T_{\text{dust}}) \) is the Planck function with the dust temperature of \( T_{\text{dust}} \). Adopting an average dust temperature of 20 K (following Andrews & Williams 2005), a dust opacity \( \kappa_\nu = 3.4 \text{ cm}^2 \text{ g}^{-1} \) (Beckwith et al. 1990), and a gas-to-dust ratio of 100 leads to a disk mass of 0.075 ± 0.003 M\(_{\odot} \). This estimate for disk mass is consistent with standard techniques but depends on highly uncertain
2.7 rms noise, the lowest contour, and subsequent contour step for the individual molecules are as follows: 4.7 ν implies that either the disk is optically thick at 343.4 GHz and that dust grains have grown where n (see review by Williams & Cieza 2011). The JCMT/SCUBA-2 850 μm flux of EC 53 after removing the contribution of the disk implies the envelope mass is 0.86–1.25 M⊙ (see Equation (1) in Jørgensen et al. 2009). The disk to envelope mass ratio, 6%–9%, implies that EC 53 could be a late Class 0 (1%–10%) or an early Class I source (20%–60%) (Jørgensen et al. 2009). This is consistent with the early Class I stage (Dunham et al. 2015) derived from the bolometric temperature (Tbol = 130 K) of the SED, although a continuum radiative transfer model is needed to estimate more accurate disk and envelope masses.

![Figure 3](image-url)

**Figure 3.** Integrated intensity maps for the detected molecular lines toward EC 53. The background image is the zoom-in of Figure 1. The thick solid and dashed gray lines indicate the disk and outflow directions, respectively. The blue dashed curvature in the bottom right panel indicates the outflow cavity wall traced by a near-IR observation (Hodapp et al. 2012). The ellipses on the bottom left corner represent the synthesized beam. The scale bar of 500 au is at the bottom right of the weak CCH. The CH3OH and weak CCH lines are marginally detected (see Table 1). Those lines of the individual molecules are stacked to get a higher S/N. The 1σ rms noise, the lowest contour, and subsequent contour step for the individual molecules are as follows: 4.7 mJy beam⁻¹ km s⁻¹, 3σ, and 1σ for C34S, 2.7 mJy beam⁻¹ km s⁻¹, 3σ, and 1σ for CH3OH, 4.4 mJy beam⁻¹ km s⁻¹, 3σ, and 1σ for weak CCH, 4.6 mJy beam⁻¹ km s⁻¹, 5σ, and 2σ for H13CO⁺, 4.3 mJy beam⁻¹ km s⁻¹, 5σ, and 3σ for C17O, 5.6 mJy beam⁻¹ km s⁻¹, 5σ, and 3σ for CCH.

In this section, we infer the morphology of the circumstellar material by measuring gas kinematics in the spectral images of emission lines. The different emission lines probe the disk, infall, and outflows of the source, as described below. A source velocity of 8.5 km s⁻¹ is adopted throughout this analysis, based on the rotation profile of the C17O line along the disk direction (Section 3.2.1). This value is similar to a previous measurement of ~8.35 km s⁻¹ using N2H⁺ 1–0 line emission measured with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) data that has a beam size of 7″ (Lee et al. 2014), with a slight offset that may be explained because the N2H⁺ species is depleted at the source position (Figure 4).

Figure 3 shows integrated intensity maps for the detected molecular lines toward EC 53. H13CO⁺ 4–3, C17O 3–2, and CCH N = 4–3, J = 7/2–5/2, F = 4–3, F = 3–2 (in the bottom panels) consist of compact emission near the continuum peak and more extended emission while C34S 8–7, CH3OH, and other weak CCH lines (in the top panels) show only compact and weak emission near the continuum source. Those weak CH3OH and CCH lines are stacked individually to get a higher S/N. The observed lines are listed in Table 1.

The integrated intensity maps of the H13CO⁺ and C17O lines generally show similar distributions. Both lines have redshifted and blueshifted components in the north and south, respectively, as shown in the intensity-weighted velocity map (Figure 5).
velocity channel maps of C$^{17}$O and H$^{13}$CO$^+$ (Figures 6 and 7) show that the redshifted components (9.00–9.75 km s$^{-1}$) have decreasing velocity with the distance from the protostar. Such a profile is expected for redshifted emission from infalling (accreting) material, as also seen in the Class I source L1489 IRS (Yen et al. 2014). The same trend is also observed in the C$^{18}$O blueshifted components (8.00–7.25 km s$^{-1}$) near the protostar ($r < 1''$). On the other hand, the blueshifted velocity (8.50–7.75 km s$^{-1}$) increases with the distance from the protostar at $r > 1''$. This implies that the blueshifted emission at the scale of $r > 1''$ traces the gas in the outflow cavity wall (e.g., Arce et al. 2013). The blueshifted monopolar outflow could be due to an asymmetric structure of the circumstellar environment (Loinard et al. 2013).

At the continuum peak, absorption against the continuum emission is detected in the H$^{13}$CO$^+$ and strong CCH lines, while self absorption is detected in the C$^{17}$O line (Figure 8). This deep absorption below the continuum level in the H$^{13}$CO$^+$ and strong CCH lines is redshifted, tracing the infalling envelope material (Evans et al. 2015). The high velocity ($|\Delta V| > 1$ km s$^{-1}$ from the source velocity) emission feature detected in the C$^{17}$O line (the red spectrum in Figure 8), which may trace the disk rotation, is missing in the H$^{13}$CO$^+$ line. Figure 7 shows that there is no H$^{13}$CO$^+$ line emission within $\sim$0.2′′ from the protostar. The related chemistry for this phenomenon is discussed in Section 4.2.

The strong CCH line emission (the bottom right contour image of Figure 3) seems to trace the outflow cavity walls. The stream to the east, which appears distributed along the blueshifted outflow cavity wall, is also seen in the near-IR narrowband image covering the H$_2$ emission (Hodapp et al. 2012). Another stream toward the north direction looks like a mirror image of the eastward stream with respect to the disk midplane (the solid gray line in Figure 3), which could imply that the northward stream might trace the redshifted outflow cavity wall. CCH emission along the outflow cavity walls is also found in L1527, IRAS 15398–3359, and L483 (Oya et al. 2014; Sakai et al. 2014; Oya et al. 2017).

The CH$_3$OH and other weak CCH lines are marginally detected (see Table 1). While the CH$_3$OH lines are detected near the continuum peak, the weak CCH lines are missing toward the continuum source, instead peaking at 0′′.55 from the continuum peak along the disk direction. The same phenomenon has been observed in other sources: in L1527, IRAS 15398–3359, and L483 the CCH is also depleted near the continuum peak and has strong emission off the peak (Oya et al. 2014, 2017; Sakai et al. 2014). The CCH molecule reacts with H$_2$ at warm temperatures (see e.g., Aikawa et al. 2012) and could be destroyed by those gas phase reaction in the warm and dense inner envelope and/or frozen on the dust grain in the cold and dense disk.

The C$^{34}$S 8–7 line seems to trace the dense molecular gas near the continuum peak as well as in the outflow cavity wall. The SiO 7–6 line was also observed but not detected.

3.2.1. Kinematics of C$^{17}$O 3–2: Disk versus Infalling Rotating Envelope?

The rotation profile along the disk direction provides evidence of the kinematics of the disk. Figure 9 shows velocity channel maps for C$^{17}$O near the continuum peak. The innermost regions have a position–velocity distribution that would be expected for a disk. Beyond 0′′.5 along the position angle of 60° (the black solid line in Figure 9), the spatial distribution of redshifted components (9.75 and 9.50 km s$^{-1}$) implies that this emission might not be associated with the disk. In the following analysis, we fit the rotation profile only within 0′′.5. The highest velocity components are close to the protostar, and the models with different position angles from 30° to 60° do not show significant variation in the rotation profile.

Figure 10 shows the position–velocity diagram along the disk (left) and the rotation velocity profiles (right) of EC 53. The power-law index that fits the velocity profile is $-2.1 \pm 2.2$. If the highest blueshifted point is excluded, the best-fit power law is $-1.1 \pm 0.7$, indicative of the rotating infalling envelope under the constraint of angular momentum conservation (Sakai et al. 2014). However, our current observation with large scatter and a low S/N cannot rule out a rotational profile produced by the Keplerian disk. The range of the rotation velocity corresponds to the Keplerian motions with the protostellar masses of 0.2 and 0.4 $M_\odot$ when we adopted the inclination of 35°. Since the protostar is still young and the envelope massive, the present-day protostellar mass may be much lower than the final mass after stellar assembly is complete.

4. Discussion

4.1. Dust Grain Growth

The observed 873 μm continuum emission is mainly from dust thermal emission. In the continuum images produced with uniform weighting, the peak intensity and the spectral index at the continuum peak are 69.3 ± 0.4 mJy beam$^{-1}$ and 1.9 ± 0.3, respectively. The spectral index lower than 2 cannot be explained by non-thermal emission, as VLA 4.5 and 7.5 GHz observations (with a beam size of $\sim$0″.4, Ortiz-León et al. 2015) indicate that the 873 μm flux from the non-thermal emission is lower than 0.2 mJy. Therefore, the spectral index of 1.9 ± 0.3 implies that the continuum emission is optically thick and/or
Figure 5. Integrated intensity maps (contours) and intensity-weighted velocity maps (images) for the detected molecular lines toward EC 53 except for CCH. The contours are the same as in Figure 3.

Figure 6. Velocity channel maps of C$^{17}$O 3–2. The data are extracted from the Briggs-weighting image. The contour levels start from 4σ and increase in step of 2σ ($1\sigma = 3.85$ mJy beam$^{-1}$). The gray lines and circles are plotted in step of 30' and 1', respectively, to identify the position of emission clearly. The synthesized beam and the scale bar of 500 au are presented at the bottom left and right, respectively, in the panel with the velocity of 6.75 km s$^{-1}$. 
that the power-law index of dust opacity is lower than 1 in the isothermal condition.

The submillimeter continuum spectral index can be used to derive the properties of emitting sources and dust grains. The low spectral index (1.9 ± 0.3) for the dust continuum emission indicates that the compact continuum emission could be emitted from the disk. On the other hand, the spectral index derived from the Atacama Compact Array (ACA) images of EC 53 in bands 6 and 7, which trace the envelope of EC 53, is about 2.5 (W. Park, 2019, in preparation). Continuum emission images at 1.1 mm and 3 mm toward two Class I sources Elias 29 and WL 12 show that the spectral indices in the disk are typically lower than 2, while in the envelope are typically higher than 2.5 (Miotello et al. 2014). Figure 11 shows the optical depth and the power-law index of dust opacity, β, for given dust temperatures reproducing the observed spectral index of 1.9 ± 0.3. When we adopt the dust temperature of 20 K and β = 1, which are used for the calculation of the disk mass, the average optical depth of dust continuum is 1.8 ± 0.2 (see the blue circle in Figure 11). If this optical depth is considered, the disk mass derived by Equation (1) is smaller than the actual value by a factor of two. On the other hand, if we know the dust temperature and the optical depth of dust continuum, then we can derive β, which constrains the dust properties; grain growth in the disk reduces the power-law index of dust opacity (e.g., Natta et al. 2007).

The optical depth of the dust continuum can be derived from a molecular line. As shown in the integrated intensity maps for the detected molecular lines (Figure 3), the emission peaks of all the molecular lines are off the continuum peak. Figure 12 shows the C$^{17}$O 3–2 intensity map integrated over the velocity from 1.0 to 1.5 km s$^{-1}$ with respect to the source velocity. This integrated intensity map was produced using the uniform weighting to trace how the C$^{17}$O emission is distributed near the continuum peak, by excluding the contribution of the extended emission. The C$^{17}$O line emission is clearly depleted near the continuum peak and peaks around 0′′13 from the continuum peak. This phenomenon was also observed in TMC 1A (Harsono et al. 2018) and V883 Ori (Lee et al. 2019). A high optical depth and strong emission of the dust continuum can reduce the intensity of the molecular line emission; the
observed line intensity is reduced by $\exp(-\tau_c)$ with the dust optical depth of $\tau_c$ (Yen et al. 2016; Lee et al. 2019).

We adopt a simple thin disk with power-law distributions for the continuum optical depth $\tau_c(r)$ and the dust temperature $T_{dust}(r)$:

$$\tau_c(r) = \tau_{0.1}(\frac{r}{0.1})^{-\psi},$$

$$T_{dust}(r) = T_{0.1} \sqrt{\frac{0.1^\psi}{r}},$$

where $\tau_{0.1}$ and $T_{0.1}$ are the continuum optical depth and dust temperature at 0.1. We test three power-law indices of optical depth: $\psi = 1.0, 1.5,$ and $2.0$. The solid lines in Figure 13 indicate the models producing the observed 873 $\mu$m intensity at the continuum peak (69.3 $\pm$ 0.4 mJy beam$^{-1}$). The emission from the inclined thin disk (inclination = 35°) are convolved with the observed beam.

The C$^{17}$O intensity within 0.5 (Figure 9) is lower than 45 mJy beam$^{-1}$, which corresponds to a brightness temperature

Figure 9. Zoom-in of Figure 6. The gray circle indicates the radius of 0.5.

Figure 10. Position–velocity diagram (left) and rotation profile (right) of C$^{17}$O 3–2 along the disk direction with a position angle of 60°. Left: the image and red contours indicate the observed C$^{17}$O intensity extracted from the Briggs-weighting image. The contours start from 4σ in step of 1σ (1σ = 3.8 mJy beam$^{-1}$). The dashed yellow lines represent the Keplerian motion with a protostellar mass of 0.3 $M_\odot$. Right: the red (blue) points indicate the peak positions along given redshifted (blueshifted) velocity channels as shown in the yellow cross in the left panel. Three dotted lines represent the Keplerian motion with a protostellar mass of 0.4 (top), 0.3 (middle), and 0.2 $M_\odot$ (bottom), respectively. When these data are fit with a power-law function, the power-law index is $-2.1 \pm 2.2$ (black solid line).
The optical depth at 873 μm (τ) and the power-law index of dust opacity (β) producing the spectral index (α) of 1.9 for the given dust temperatures: 20 (blue), 50 (black), and 80 K (red), respectively. The blue circle indicates the τ producing α = 1.9 for the temperature of 20 K and β = 1 used to calculate the disk mass (Section 3.1) while the black circle indicates the β producing α = 1.9 for the temperature of 50 K and τ = 1.4 derived from the thin disk model (see Table 2).

Figure 11. Optical depth at 873 μm (τ) and the power-law index of dust opacity (β) producing the spectral index (α) of 1.9 for the given dust temperatures: 20 (blue), 50 (black), and 80 K (red), respectively. The blue circle indicates the τ producing α = 1.9 for the temperature of 20 K and β = 1 used to calculate the disk mass (Section 3.1) while the black circle indicates the β producing α = 1.9 for the temperature of 50 K and τ = 1.4 derived from the thin disk model (see Table 2).

Our models with the dust temperature of 50–55 K and dust optical depth of 1.1–1.6 at the radius of 0″1 can reproduce the C17O emission peak around 0″13 (see the circles in Figure 13 and Table 2). The thin dust disk with a truncated radius of 0.13″ can reproduce the observed continuum flux of 139.7 mJy as well as the disk size measured with “imfit.” The entire dust disk is optically thick, and thus, the C17O emission peaks at the dust disk radius. When the dust opacity of 3.4 cm² g⁻¹ at 343.4 GHz (Beckwith et al. 1990) and gas-to-dust ratio of 100 are adopted, the models show the disk mass is 0.1 M☉ with an uncertainty by a factor of two, which is similar to the disk mass of 0.075 M☉ (see Section 3.1). Note that grain growth can change the dust opacity (e.g., Ricci et al. 2010), and thus, the disk mass. The calculated dust mass would also be 3.3 times lower if we use 50 K instead of 20 K for the average dust temperature in the disk.

For the dust temperature of ∼50 K and the continuum optical depth of ∼1.4 near the continuum peak in our model, the power-law index of the dust opacity (β) must be lower than 0.2 ± 0.6 to reproduce the observed spectral index of 1.9 ± 0.3 (see the black circle in Figure 11). This suggests that the maximum size of dust grains should be larger than centimeter sizes (e.g., Ricci et al. 2010; Testi et al. 2014). The large disk mass of about 0.1 M☉ and the large grain size imply...
Notes.

a Best fit parameters in the thin disk models (see Figure 13).

b The truncated radius of disk producing the observed continuum flux (139.7 mJy).

c The surface area weighted temperature within a disk ($r < r_{\text{max}}$).

d The disk mass from the thin disk model with the dust opacity of 3.4 cm$^2$ g$^{-1}$ (Beckwith et al. 1990) and the gas-to-dust ratio of 100.

4.2. Water and CO Snow Lines

Figure 14 shows the spectral maps of H$_{13}$CO$^+$ and C$^{17}$O on top of the image of the CH$_3$OH integrated intensity map. Outside of the CH$_3$OH emission area, the H$_{13}$CO$^+$ line has a similar intensity to the C$^{17}$O line. However, the H$_{13}$CO$^+$ line emission is depleted near the continuum peak, where the methanol lines emit. On the other hand, the C$^{17}$O line is still strong and broad near the continuum peak where the H$_{13}$CO$^+$ emission completely disappears. The CH$_3$OH line might emit from the disk or infalling rotating inner envelope traced by C$^{17}$O because the CH$_3$OH line has a similar line width to that of the C$^{17}$O line. The emission peak of CH$_3$OH is offset from the continuum peak probably due to the optically thick continuum emission, as also shown in the C$^{17}$O emission distribution. The anticorrelation between the H$_{13}$CO$^+$ and CH$_3$OH emission was also detected in IRAS 15398-3359 and may be caused by the destruction of H$_{13}$CO$^+$ by water, which evaporates simultaneously with CH$_3$OH (Jørgensen et al. 2013). The methanol emission is known to be related closely with water emission (Bjerkeli et al. 2016). However, the observed CH$_3$OH emission is extended up to ~0$''$35 (see Figure 14), which is an order of magnitude larger than the water snow line expected from the current luminosity. In the thin disk model described above, the water snow line (100 K) is located around 0$''$03.

To measure the abundance of methanol, we first extracted the CH$_3$OH spectra with an aperture of 0$''$6. We then reproduced this spectrum with a simple LTE model using molecular data from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2001). The model includes the dust continuum and opacity and assumes a line width of 2 km s$^{-1}$. The molecular hydrogen column density of $\sim$10$^{25}$ cm$^{-2}$ is estimated from the dust continuum flux measured with the same 0$''$6 aperture when the dust opacity of 3.4 cm$^2$ g$^{-1}$ (Beckwith et al. 1990), gas-to-dust ratio of 100, and the dust temperatures of 30, 50, and 70 K are adopted. The derived methanol column density and abundance are $\sim$10$^{15}$ cm$^{-2}$ and $\sim$10$^{-10}$, respectively (see Figure 15).

The methanol emission from the much larger outburst of V883 Ori provides a useful comparison for that from EC 53. The derived methanol abundance for EC 53 is two orders of magnitude lower than the CH$_3$OH abundance of $\sim$10$^{-8}$ for V883 Ori (Lee et al. 2019) although the physical size of the methanol emission regions are similar for V883 Ori and EC 53. In both cases, the methanol abundance may be underestimated by an order of magnitude because of the optical depths of dust continuum and methanol itself (van ’t Hoff et al. 2018; Lee et al. 2019).

The difference in abundance between EC 53 and V883 Ori, despite the similar size of methanol emission, might be related to the repeated outbursts and the 2D structure of the sublimation region. The water/methanol sublimation occurs over the 2D structure in the disk (van’t Hoff et al. 2018; Lee et al. 2019); the snow line extends to much larger radii at the disk surface than at the disk midplane. During the quiescent phase, the methanol freezes back onto grain surfaces very efficiently in the disk midplane but much more slowly at the disk surface, where the density is much lower. As a result, if there were powerful burst events in the past in EC 53, the surface snow line could be very large, despite a much smaller snow line at the disk midplane because of the low current luminosity. This will make the derived abundance of gaseous CH$_3$OH low compared with the size of emission in EC 53. In contrast, V883 Ori has an ongoing outburst with the luminosity greater than that of EC 53 in the quiescent phase by two orders of magnitude. As a result, the snow line is large even at the disk midplane, resulting in the higher abundance of gaseous methanol in V883 Ori.

In summary, the different timescales for freeze-out between the disk midplane and surface may explain why the methanol emission region extends far beyond the location of the water snow line expected from the current luminosity of EC 53, despite the low overall abundance compared with V883 Ori. The repeated accretion bursts in EC 53 may extend the water snow line, and the disk surface will retain the larger snow line for a longer time than the disk midplane.
Grain growth in the disk midplane could also contribute to increasing the radius of the snow line in the disk midplane. When the ratio of scale height to radius is 0.1, the density at the midplane near 0″1 is \(10^{11} \text{ cm}^{-3}\). If we adopt the typical ISM grain size (0.1 \(\mu\)m) and the typical abundance of the dust grain with respect to the molecular hydrogen \(\sim 10^{-15}\), then all methanol molecules freeze out onto the dust grain within a few days (Lee et al. 2004). However, the freeze-out timescale could be longer than a few years when the maximum grain size is larger than 1 cm (see Section 4.1), as the total surface area of grains would then be reduced by a factor of \(\sim 300\), assuming that the total grain mass is conserved, and the minimum size of grain and the power-law index of grain size distribution are 0.1 \(\mu\)m and \(-3.5\), respectively. This freeze-out timescale is longer than the periodicity of 1.5 yr in the accretion onto EC 53 (Yoo et al. 2017). The CH\(_3\)OH emission could trace the water snow line constructed during the burst phase of the period, when the luminosity is four times brighter (Yoo et al. 2017) and the water snow line would then be two times larger, or \(\sim 0.06″\) (Min et al. 2011; Jørgensen et al. 2015; Visser et al. 2015). Although the CH\(_3\)OH emission could extend further than 0″06 at the disk surface because of the high temperature and low density in the irradiated disk (van ’t Hoff et al. 2018; Lee et al. 2019), the measured size of the CH\(_3\)OH emission requires a more extreme (factor of \(\sim 100\)) luminosity enhancement.

Figure 4 shows that the \(N_2\)H\(^+\) line emission is anticorrelated with the \(^{17}\)O 3–2 line emission. It is hard to determine accurately the size of the \(N_2\)H\(^+\) emission hole because of the low spatial resolution \(\sim 2″\) of CARMA. However, our \(^{17}\)O ALMA data (Figures 3 and 6) indicate that the \(^{17}\)O line extends to \(\sim 2″\) along the disk midplane direction. In addition, in the ACA observation (Figure 4), the full width at half maximum of the \(^{17}\)O 3–2 emission is about \(2″7\). This observed CO snow line \((\sim 1000 \text{ au})\) is also larger than that expected from the luminosities both for the quiescent and burst phases \((\sim 250 \text{ au} \text{ and } \sim 500 \text{ au}, \text{respectively})\). These CO sublimation radii (25 K) are derived from the spectral energy distribution modelings of EC 53 (Baek et al. 2019). Together, the estimated sizes of the \(^{17}\)O emission and the \(N_2\)H\(^+\) emission hole support suggestion of repeated and/or more extreme burst events in the past.

5. Summary

We carried out high-resolution ALMA observations toward EC 53. The main results are:

1. The continuum image at 873 \(\mu\)m shows that EC 53 has a massive disk \((0.075 \pm 0.003 \text{ M}_\odot)\) with centimeter-size grains, implying that a planet could form even in the early evolutionary stage to induce the observed periodic variation of accretion rate. Furthermore, the optically thick dust continuum emission in the submillimeter reduces the molecular line emission near the continuum peak.

2. The high velocity components of \(^{17}\)O 3–2 show a rotation feature along the disk direction, however, the current observation cannot constrain whether the rotation profile is associated with the Keplerian disk and/or an infalling envelope. If the Keplerian motion is adopted, the rotation profile indicates that EC 53 has a protostellar mass of \(\sim 0.3 \pm 0.1 \text{ M}_\odot\).

3. The anticorrelation of CH\(_3\)OH and H\(^{13}\)CO\(^+\) near the continuum peak could be associated with the destruction of H\(^{13}\)CO\(^+\) by evaporated water molecules.

4. The observed methanol and CO emissions are more extended than the snow lines expected due to the current luminosity, implying repeated and/or more extreme accretion burst events in the past. The luminosity and therefore the abundance of CH\(_3\)OH is two orders of magnitude lower than measured from disks undergoing larger outbursts, perhaps because the CH\(_3\)OH is frozen out at the disk midplane but is still in the gas phase in the lower-density disk surface.

This work was motivated and performed by the JCMT-Transient Team as part of a comprehensive effort to obtain and interpret time-domain submillimeter observations of star-forming regions. The authors appreciate the important contribution of the JCMT Transient Team members in observing, calibrating, and making available the JCMT submillimeter observations used for this paper. This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (grant No. NRF-2018R1A2B6003423) and the Korea Astronomy and Space Science Institute under the R&D program supervised by the Ministry of Science, ICT and Future Planning. S. L. was also supported by NAOJ ALMA Scientific Research grant No. of 2018-10B. Y.A. was supported by KAKENHI grant No. 18H05222 and NAOJ ALMA Scientific Research grant No. of 2019-13B. GJH is supported by general grant 11773002 awarded by the National Science Foundation of China.
