The disappearing envelope around the transitional class I object L43

Shin Koyamatsu1,2, Shigehisa Takakuwa3, Masahiko Hayashi4, Satoshi Mayama5, and Nagayoshi Ohashi2

1 Department of Astronomy, Graduate School of Science, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan; shin.koyamatsu@nao.ac.jp
2 Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, USA
3 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 10617, Taiwan
4 National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka-shi, Tokyo 181-8588, Japan
5 Graduate University for Advanced Studies, Shonan International Village, Hayama-cho, Miura-gun, Kanagawa 240-0193, Japan

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ABSTRACT

We present Submillimeter Array interferometric observations of the $^{12}$CO ($J = 2–1$), $^{13}$CO ($J = 2–1$), and C$^{18}$O ($J = 2–1$) lines and 225 GHz continuum emission and Submillimeter Telescope single-dish observations of C$^{18}$O ($J = 2–1$) toward L43, a protostellar object in transition from Class I to II. The 225 GHz continuum emission shows a weak ($\sim$23.6 mJy), compact ($<1000$ AU) component associated with the central protostar. Our simulated observations show that it can be explained by dust thermal emission arising from an envelope which has a hole or a constant intensity region within a few hundred AU of the protostar. This suggests the disappearance or a lower concentration distribution of the envelope on a small scale. The $^{12}$CO and $^{13}$CO emission exhibit molecular outflows to the south and north. The C$^{18}$O emission shows two molecular blobs, which correspond to the reflection nebulosity seen in near-infrared images, while there is no C$^{18}$O emission associated with the protostar. The near-infrared features are likely due to the scattering at the positions of the blobs. The visible scattering features should result from the optical thinness of the envelope material, which is consistent with the less-concentrated distribution in the continuum emission. From single-dish observations, we found that the mass of the envelope ($\sim$1.5 $M_\odot$) + protostar ($\sim$0.5 $M_\odot$) is comparable with the virial mass of $M_{\text{vir}} = 1.0 M_\odot$ within 40’. This suggests that the envelope is likely gravitationally bound. We suggest that the protostellar envelope of L43 has been disappearing by consumption through accretion, at least in the close vicinity of the protostar.

Key words: circumstellar matter – stars: formation – stars: individual (L43) – stars: low-mass – stars: protostars

Online-only material: color figures

1. INTRODUCTION

Observational and theoretical studies in the past few decades have revealed that low-mass protostars (Class 0 and Class I sources) evolve into T Tauri stars (Class II sources) surrounded by protoplanetary disks. A low-mass accreting protostar is associated with an envelope or a dense molecular cloud core, with a mass typically a few times the final stellar mass and a size of 1000–10,000 AU, while an optically visible T Tauri star is accompanied by a protoplanetary disk with a typical mass of 0.1%–1% of the star and a size of 100–1000 AU (e.g., André et al. 2000; Myers et al. 2000; Andrews & Williams 2005). Although a protostellar envelope is thought to disappear in part by accretion onto the central star–disk system, and in part by being blown away by the associated outflow in the course of its evolution from a protostar to a T Tauri star (Nakano et al. 1995), details of the disappearing processes are still poorly understood. Observations of a transitional object from an embedded protostar to a T Tauri star are crucial in order to understand the mechanism for a disappearing protostellar envelope.

There are several low-mass young stars classified as T Tauri stars but which are associated with relatively large amounts of material in their envelopes. These transitional objects are characterized by a flat spectral energy distribution (SED) in infrared wavelengths ($2.2–10\,\mu m$; Greene et al. 1994), although they are usually classified either as Class I or Class II according to their near to mid-infrared SEDs. HL Tau is an archetype flat-spectrum object with a flattened infalling envelope (Hayashi et al. 1993), while DG Tau, another representative flat-spectrum source, shows an expanding envelope (Kitamura et al. 1996). Each envelope has a similar mass of 0.03 $M_\odot$, slightly higher than the typical mass of many protoplanetary disks. Another prototypical flat-spectrum object, T Tau, still possesses 0.31–1.3 $M_\odot$ of surrounding gas (Momose et al. 1996). The structure and kinematics around the transitional objects appear to be complicated and require further studies.

L43, also called RNO 91, is one of several such transitional objects located in the Ophiuchus molecular cloud complex at a distance of $\sim$125 pc (de Geus et al. 1990). The source has a bolometric luminosity of 4.3 $L_\odot$ (Terebey et al. 1993) and a central stellar mass of 0.5 $M_\odot$ (Lebreault 1988). L43 used to be classified as a Class II object, and its bolometric temperature was estimated to be 715 K (Andre & Montmerle 1994; Chen et al. 1995). Recent data, however, show that L43 is now classified as a Class I object with a lower bolometric temperature of 337.6 K, which is still higher than that of typical Class I objects. Single-dish observations of L43 in the 850 $\mu m$ continuum emissions showed the presence of an extended ($\sim$7000 AU) dusty envelope (Shirley et al. 2000), and interferometric mosaicking observations of L43 unveiled the conspicuous U-shaped, large-scale ($>50,000$ AU) blueshifted molecular outflow toward the southeast of the driving source with a position angle of 155° (Lee et al. 2002; Lee & Ho 2005). Single-field interferometric observations of the close vicinity ($<10,000$ AU) of L43 also showed the outflow-like structure but with the orientation toward the south rather than southeast (Arce & Sargent 2006). Near-infrared images of L43 taken with the Subaru Telescope exhibit reflection nebulosity and extinction maps which might be attributed to the disk-like structure around the central star (Mayama et al. 2007). Optical polarization observations also suggest the presence of
the circumstellar disk around L43 (Heyer et al. 1990; Scarrott et al. 1993). These results show that L43 is one of the ideal objects in which to study the transition from the protostellar stage to the T Tauri stage. Table 1 summarizes the properties of L43.

In this paper, we present results of the SubMillimeter Array (SMA) observations of L43 in $^{12}$CO ($J=2-1$), $^{13}$CO ($J=2-1$), and C$^{18}$O ($J=2-1$) lines and 225 GHz continuum emission, together with the 10 m Submillimeter Telescope (SMT) observations in C$^{18}$O ($J=2-1$) line. Our analyses of the data have shown details of the molecular outflow, the dispersion of the protostellar envelope, and the circumstellar disk. We describe below the SMA and SMT observations (Section 2) and continuum and molecular-line results (Section 3). In the last section (Section 4), we will discuss the dust opacity index, the origin of the dust emission, and the physical condition of the protostellar envelope in L43.

### 2. OBSERVATIONS

L43 was observed with the compact configuration of the SMA on 2005 June 28 in $^{12}$CO ($J=2-1$; 230.538000 GHz), $^{13}$CO ($J=2-1$; 220.398684 GHz), and C$^{18}$O ($J=2-1$; 219.560358 GHz) lines, and in 1.3 mm continuum emission simultaneously. Details of the SMA are described by Ho et al. (2004). For the molecular-line observations, 128 spectral channels were assigned to spectral windows of the SMA simultaneously. Details of the SMA are described by Ho et al. (2004). For the molecular-line observations, 128 spectral channels were assigned to spectral windows of the SMA.

### 3. RESULTS

#### 3.1. 225 GHz Continuum Emission

Figure 1 shows the 225 GHz continuum map toward L43 observed with the SMA. The continuum emission is clearly detected at above the 5σ level toward the central stellar position. In addition to the main peak located at the central stellar position, there is a secondary peak 3′′ to the north. While the continuum distribution possibly suggests the presence of this and many other components in the area, we cannot confirm their existence due to the low signal-to-noise ratio (S/N) and will not discuss them further here. The peak and total flux densities of the primary component are 12.1 ± 2.4 mJy beam$^{-1}$ and 23.6 ± 2.4 mJy, respectively. Although the primary continuum component shows an apparent elongation from the northeast to southwest, a two-dimensional Gaussian fitting to the image does not provide a beam-deconvolved size and a position angle, presumably due to the low S/N.

To illustrate the nature of the dust continuum emission, the SED toward L43 is presented in Figure 2. The SED shows a fairly flat or slightly rising spectrum from near- to far-infrared, with less excess at far-infrared compared to that of a typical

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### Table 1

| Name        | Distance$^a$ (pc) | $L_{bol}^b$ ($L_\odot$) | $T_{bol}^c$ (K) | $M_\text{env}^d$ ($M_\odot$) |
|-------------|-----------------|----------------------|-----------------|-----------------------------|
| L43 (RNO 91)| 125             | 2.5 ± 0.1            | 337.6 ± 18.9    | 0.5                         |

### Table 2

| Parameter                      | Value                      |
|--------------------------------|----------------------------|
| Date                           | 2005 June 28               |
| Right ascension (J2000.0)      | 16$^h$34$^m$29$^s$33      |
| Declination (J2000.0)          | −15$^\circ$47′01″.5        |
| Number of antennas             | 7                          |
| Primary beam HPBW              | ∼56$^\prime$              |
| Baseline coverage              | 7.3–160 kJ                |
| Frequency resolution           | 812 kHz (∼1.06 km s$^{-1}$)|
| Bandwidth                      | 3.8 GHz                    |
| Flux calibrator                | Callisto                   |
| Gain calibrators               | 1743-038, 1733-130         |
| Flux (1743-038)                | 1.87 Jy (upper)$^a$, 1.93 Jy (lower)$^a$ |
| Flux (1733-130)                | 1.14 Jy (upper)$^a$, 1.19 Jy (lower)$^a$ |
| Passband calibrator            | 3±454.3                   |
| System temperature (DSB)       | ∼300–500 K                 |

Note. $^a$ “Upper” and “lower” denote the flux densities of the calibrator at the upper and lower sidebands, respectively.

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$^a$ de Geus et al. (1990).

$^b$ Bolometric luminosity (Chen et al. 2009).

$^c$ Bolometric temperature (Chen et al. 2009).

$^d$ Central stellar mass (Levreault 1988).

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$^6$ The Submillimeter Array (SMA) is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.
Class I object. This is consistent with the interpretation that L43 is in a transitional phase from a protostar to a T Tauri star. The three data points at millimeter wavelengths (shown in red in Figure 2) were taken from interferometric observations (including the present work) with beam sizes of 4′′−13″, while data points at far-infrared were taken from single-aperture observations with 40″−70″ beam sizes (Chen et al. 2009). It is clear that values at millimeter wavelengths are lower than those expected from extrapolation of the measurements at far-infrared wavelengths. This is likely because of artifacts caused by the interferometric observations resolving out extended continuum emission. In other words, the millimeter interferometric observations selectively detected a central part of the circumstellar structure rather than the extended dust emission. We discuss the properties and origin of dust continuum emission at millimeter wavelengths in Sections 4.1 and 4.2.

3.2. CO Line Emission

Figures 3–8 show velocity channel maps and integrated intensity maps of 12CO (J = 2–1), 13CO (J = 2–1), and C18O (J = 2–1) lines. We adopt the systemic velocity of the protostar L43 as $V_{\text{LSR}} = 0.52 \pm 0.01$ km s$^{-1}$, which was derived from the Gaussian fitting to the single-dish DCO$^+$ (J = 3–2) and C18O (J = 2–1) spectra toward L43 (Chen et al. 2009).
be south of the protostellar position. In the redshifted velocity, the \(^{12}\)CO emission primarily shows an elongated feature northeast of the protostar. In addition, two weaker features are seen at \(\sim 7''\) southeast and \(\sim 15''\) northwest of the protostar. The redshifted emission appears to be located on the opposite side from the blueshifted one. The \(^{12}\)CO emission around the systemic velocity appears to be associated with the central protostar. This emission, however, is largely resolved out, as mentioned above, and we will not discuss it in this paper. The indication that blueshifted and redshifted components are located to the south and north, respectively, is roughly consistent with the previous studies of the outflow associated with L43 (Lee et al. 2002; Lee & Ho 2005; Arce & Sargent 2006). We thus consider that the \(^{12}\)CO \((J = 2\rightarrow 1)\) emission selectively traces the molecular outflow driven by L43 in the same manner as typical protostars.

\subsection{\(^{13}\)CO \((J = 2\rightarrow 1)\) Emission}

Figure 5 shows the channel maps of less optically thick \(^{13}\)CO \((J = 2\rightarrow 1)\) emission. The \(^{13}\)CO emission was detected in the velocity range from \(V_{\text{LSR}}\) \(= -3.5\) to \(3.2\) \(\text{km}\) \(\text{s}^{-1}\); the blueshifted emission range is smaller than that of the \(^{12}\)CO emission, which reflects the smaller optical depth of the \(^{13}\)CO line. At blueshifted channels (panels (j)-(l)), the emission components are located south of the protostellar position, which is roughly consistent with the \(^{12}\)CO emission. The differences in some details may arise from the less optically thick nature of the \(^{13}\)CO emission. The elongated feature seen in the \(^{13}\)CO emission at the redshifted channels (panels (n) and (o)) is also seen in the \(^{12}\)CO emission at the same velocities. On the other hand, at the channels around the systemic velocity (panels (l) and (m)), where the \(^{12}\)CO emission may largely be resolved out, we still see the strong \(^{13}\)CO emission confined to a few features. This is because the optical depth of its \(^{13}\)CO emission is thinner than that of the \(^{12}\)CO emission, which allows us to selectively detect compact features. This fact becomes clearer in C\(^{18}\)O maps below, which is the optically thinnest line of the three.

The integrated intensity maps of the \(^{13}\)CO \((J = 2\rightarrow 1)\) emission are also shown in Figure 6, where the integrated velocity ranges are \(-3.5\) to \(-0.2\) \(\text{km}\) \(\text{s}^{-1}\), \(-0.2\) to \(1.0\) \(\text{km}\) \(\text{s}^{-1}\), and \(1.0\) to \(3.2\) \(\text{km}\) \(\text{s}^{-1}\) for blueshifted, systemic, and redshifted velocities, respectively. In the blueshifted velocity, \(^{13}\)CO emission shows an extended feature with two peaks (\(\sim 7''\) southwest and \(\sim 6''\) southeast). As with the \(^{12}\)CO emission, the blueshifted components tend to be located south of the protostellar position. In the redshifted velocity, the \(^{13}\)CO emission also traces the elongated feature identified in the \(^{12}\)CO map. We interpret that, at these velocity ranges, \(^{13}\)CO emission traces the blueshifted and redshifted outflows as the \(^{12}\)CO emission does. Around the systemic velocity, the \(^{13}\)CO emission has another feature at \(\sim 8''\) south of the protostellar position, which is not visible in the \(^{12}\)CO emission. The reason why this other feature is visible only in the \(^{13}\)CO emission is that the \(^{13}\)CO emission is optically thinner than the \(^{12}\)CO emission. This feature may be an envelope component, which is resolved out in the \(^{12}\)CO map.

We thus conclude that the origin of the \(^{12}\)CO \((J = 2\rightarrow 1)\) and \(^{13}\)CO \((J = 2\rightarrow 1)\) emission is mainly the blueshifted and redshifted outflow components. We consider that our data resolve the most central part of the \(U\)-shaped outflow traced by \(^{12}\)CO \((J = 1\rightarrow 0)\) (Lee et al. 2002). In the case of the \(^{13}\)CO emission, the envelope components may be detected around the systemic velocity, and we will confirm this in the following section with the least optically thick C\(^{18}\)O \((J = 2\rightarrow 1)\) emission.

\subsubsection{C\(^{18}\)O \((J = 2\rightarrow 1)\) Emission}

Figure 7 shows the velocity channel maps of the C\(^{18}\)O \((J = 2\rightarrow 1)\) emission, which is detected in three channels around the systemic velocity (panels (l)-(n)). It is clear that the line width of the C\(^{18}\)O emission line is much narrower than those
Figure 3. Velocity channel maps of the $^{12}$CO ($J = 2\rightarrow 1$) line emission in L43 observed with the SMA. The contour levels are from $5\sigma$ in steps of $3\sigma$ ($1\sigma = 153\text{ mJy beam}^{-1}$). The central velocity of each channel is shown in the top left in units of km s$^{-1}$. The crosses indicate the peak position of the 225 GHz continuum emission in Figure 1, and the filled ellipse in the bottom right corner in panel (p) shows the synthesized beam ($4.4' \times 3.3'$; P.A. $= 19^\circ$). The open circles show the field of view at the frequency of $^{12}$CO ($\sim 54.5'$).

(A color version of this figure is available in the online journal.)

Figure 8 shows the total integrated intensity map of the $^{18}$O ($J = 2\rightarrow 1$) emission observed with the SMA and the near-infrared images of L43 taken with the Subaru Telescope (Mayama et al. 2007). Two $^{18}$O emission regions, Blobs 1 and 2 mentioned above, are detected above $11\sigma$ and $7\sigma$, respectively. There is no emission component seen toward the protostellar position, where the 225 GHz continuum emission is detected. Previous observations of Class 0 and Class I protostars such as B335 and L1527 show that there are intense ($\gtrsim 1\text{ Jy beam}^{-1}$) $^{18}$O emission components associated with the central protostars (Jørgensen et al. 2007; Yen et al. 2010, 2011). These $^{18}$O components associated with Class 0 and I protostars have been naturally considered to be molecular envelopes surrounding protostars, indicating that the $^{18}$O emission is an excellent tracer for protostellar envelopes. Although there is no $^{18}$O emission component seen toward L43, it does not necessarily mean there is no $^{18}$O emission around L43; it is possible there is still $^{18}$O emission around L43, but most of it was resolved out by SMA. In fact, the $^{18}$O integrated intensity map obtained with SMT, shown in Figure 9, shows that there is $^{18}$O emission detectable around L43, although there is no strong peak at the protostellar position of L43. According to the comparison with the spectra toward the center of L43 obtained with SMT and SMA, the missing flux of $^{18}$O ($J = 2\rightarrow 1$) observed with SMA is estimated to be 92%. Importantly, the SMT $^{18}$O map also shows that there is no $^{18}$O integrated
intensity peak at the position of the L43 protostar, suggesting that the C18O emission is not centrally concentrated at the position of the L43 protostar. This less-concentrated distribution of the C18O emission around the L43 protostar is the reason why most of the C18O emission was resolved out in the SMA observations.

The reflection nebulosity associated with L43 is confirmed in near-infrared images (e.g., Mayama et al. 2007). According to the comparison of the C18O emission with the Subaru K-band and H−K images, these C18O blobs correlate well with the reflection nebulosity. In overlaying the SMA and the Subaru images, we assume that the SMA continuum peak position measured from a two-dimensional Gaussian fitting coincides with the peak position of the K-band image, which represents the protostellar position of L43. In the near-infrared images, Blob 1 corresponds to S, and Blob 2 is located close to L and is located between P and G. The “dark lane” in the near-infrared images corresponds to the valley between blobs in the C18O map. Accepting the LTE condition and the optically thin C18O (J = 2−1) emission, the integrated intensity in the unit of K km s\(^{-1}\) (≡ \(\int T_{\text{mb}} dv\)) were converted into the C18O column densities as

\[
N_{\text{mol}} = \frac{8\pi v^3}{c^3} \frac{1}{g_a A} \exp(-E_u/kT_{\text{ex}}) \frac{Z(T_{\text{ex}})}{\exp(hv/kT_{\text{bg}})} \int T_{\text{mb}} dv \left( J(T_{\text{ex}}) - J(T_{\text{bg}}) \right),
\]

where

\[
J(T) = \frac{hv/k}{\exp(hv/kT) - 1}.
\]

In the above expressions, \(h\) is the Planck constant, \(k\) is Boltzmann’s constant, \(c\) is the speed of light, \(v\) is the line frequency, \(T_{\text{ex}}\) is the excitation temperature, \(T_{\text{bg}}\) is the background radiation temperature, \(A\) is the Einstein A-coefficient, \(Z(T_{\text{ex}})\) is the partition function, \(E_u\) is the rotational energy level of the upper energy state, \(g_a\) is the statistical weight of the upper energy state, and \(\int T_{\text{mb}} dv\) is the integrated line intensity. The C18O molecular parameters were taken from Schöier et al. (2005). C18O column densities are converted into H\(_2\) column densities (≡ \(N_{\text{H}_2}\)) using the C18O molecular abundance (≡ \(X_{\text{C}^{18}\text{O}}\)) as \(N(\text{H}_2) = N_{\text{mol}}/X_{\text{C}^{18}\text{O}}\). In accordance with Chen et al. (2009), we assumed \(X_{\text{C}^{18}\text{O}} = 3.1 \times 10^{-3}\) taking account of the C18O depletion factor of ∼15. When \(T_{\text{ex}}\) is 10 K, \(N(\text{H}_2)\) at the positions of Blobs 1 and 2 is estimated to be \(1.0 \times 10^{23}\) cm\(^{-2}\) and \(7.2 \times 10^{22}\) cm\(^{-2}\), respectively. On the other hand, \(N_{\text{H}_2}\) is expressed using color excess by dust particles as

\[
N_{\text{H}_2} = N(\text{H}) + 2N(\text{H}_2) = 4.77 \times 10^{21} E(B - V) \text{ cm}^{-2}.
\]

Assuming \(A_V/E(B - V) \sim 3\) and \(A_K/A_V = 0.15\) (Scheffler & Eissner 1987), derived column densities of molecular hydrogen translate into dust extinction in the K-band as follows:

\[
A_K = 0.189 \left( \frac{N(\text{H}_2)}{1.0 \times 10^{21} \text{ cm}^{-2}} \right).
\]

The derived physical parameters of Blobs 1 and 2 are summarized in Table 5.

The dust extinction of >10 mag in the K band allows us to observe scattered light at the positions of the blobs. In the case that the blobs are located on the near side with respect to the position of the central star from the observer’s point of view, however, the scattered light would be totally obscured by the blobs themselves. Therefore, the blobs would be located on the

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**Figure 4.** Integrated intensity maps of the \(^{12}\text{CO} (J = 2−1)\) line emission in L43 observed with the SMA. Each panel shows the integrated intensity map over (a) blueshifted (panels (b)–(l) in Figure 3), (b) systemic (panel (m)), and (c) redshifted (panels (n)–(p)) channels, respectively. The contour levels are from 3σ in steps of 3σ, where the 1σ noise levels are 0.563 Jy beam\(^{-1}\) km s\(^{-1}\), 0.170 Jy beam\(^{-1}\) km s\(^{-1}\), and 0.294 Jy beam\(^{-1}\) km s\(^{-1}\), respectively. The crosses indicate the peak position of the 225 GHz continuum emission in Figure 1, and the filled ellipse in the bottom right corner in panel (c) shows the synthesized beam (4′/4 × 3′/3; P.A. = 19°). The open circles show the field of view at the frequency of \(^{12}\text{CO} (∼54″5)\).

(A color version of this figure is available in the online journal.)

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**Table 5.** Physical Properties of the C18O Blobs

| Component | (Δx,Δy)\(^a\) (arcsec) | θ\(^b\) (arcsec) | \(N_{\text{H}_2}\)\(^c\) (cm\(^{-2}\)) | \(A_K\)\(^d\) (mag) |
|-----------|---------------------------|-----------------|-----------------|-----------------|
| Blob 1    | (−0′′9, −8′′0)            | 6′′5 × 4′′8     | 1.0 × 10\(^{23}\) | 19.6            |
| Blob 2    | (−3′′2, −0′′4)            | 6′′3 × 4′′8     | 7.2 × 10\(^{22}\) | 13.6            |

**Notes.**

\(a\) Offset position from the central protostar.

\(b\) FWHM size of the two-dimensional Gaussian fitting (major and minor axes).

\(c\) Peak column density of molecular hydrogen toward each component.

\(d\) Extinction at K-band.
Figure 5. Velocity channel maps of the $^{13}$CO ($J = 2–1$) line emission in L43 observed with the SMA. The contour levels are from $3\sigma$ in steps of $2\sigma$ ($1\sigma = 151$ mJy beam$^{-1}$). The central velocity of each channel is shown in the top left in units of km s$^{-1}$. The crosses indicate the peak position of the 225 GHz continuum emission in Figure 1, and the filled ellipse in the bottom right corner in panel (p) shows the synthesized beam (4$.''3 \times 3$''.4; P.A. = 16$''). The open circles show the field of view at the frequency of $^{13}$CO ($\sim$57'').

(A color version of this figure is available in the online journal.)

far side, and we would observe the backward scattering at the blobs. The $H-K$ color image can also be interpreted in the same manner. The west sides of the blobs, which correspond to the far sides with respect to the central protostar, spatially correspond to the green regions in the $H-K$ image. This is because shorter waves are scattered at the near sides, which correspond to the east sides. Therefore, only longer waves can reach and are scattered at the far sides. Our comparison of these images suggests that the envelope material is so transparent that we can observe the near-infrared emission from the star. It also indicates that the dark lane seen in near-infrared images is not a shadow of material such as a circumstellar disk, but a gap in the material. More details of the nature of the C$^{18}$O envelope in L43 will be discussed later.

4. DISCUSSION

4.1. Dust Opacity Index $\beta$

The slope of the dust thermal emission provide us with information about the nature of dust particles through dust opacity indices. If we assume a single-temperature optically thin dust emission, then the flux density is expressed as

$$F_\nu \propto \kappa_\nu B_\nu(T_d) \propto \nu^\beta,$$  \hspace{1cm} (5)

where $B_\nu(T_d)$ is the Planck function, $T_d$ is the dust temperature, and $\kappa_\nu$ is the dust opacity at a frequency $\nu$. The dust opacity index $\beta$ can be estimated from a power-law fitting to $\kappa_\nu \propto F_\nu/B_\nu(T_d)$. We performed a $\chi^2$ fitting to the single-dish and interferometric measurements separately because of the gap between millimeter measurements using interferometer and far-infrared ones using the single-dish measurement mentioned above. As far-infrared measurements, two flux densities at 450 $\mu$m and 850 $\mu$m shown in blue in Figure 2 are used, since these measurements were obtained simultaneously with SCUBA, and their relative intensities are reliable. The power-law indices $\beta$ are derived to be 2.8 for the far-infrared measurements and 0.46 $\pm$ 0.47 for millimeter measurements with $T_d = 10$ K. Since there are only two measurements in far-infrared wavelengths, no error in $\beta$ arises in fitting.
The assumption of higher temperature decreases the value of $\beta$. If we assume $T_d = 30$ K, $\beta$ would be $1.6$ and $0.17 \pm 0.49$ for far-infrared and millimeter measurements, respectively. The difference in the beam sizes may have an influence on the flux measurements at millimeter wavelengths because of the missing flux. We roughly estimated this effect based on the minimum baseline length of each observation and our envelope models (see Section 4.2 for the details of our models). The measured flux density with the SMA is $\sim 50\%$ lower than those measured with the larger beams of the OVRO observations in the worst case scenario. If we take this into consideration, $\beta$ at millimeter wavelengths is estimated to be $1.0 \pm 0.3$ at most.

The value of $\beta$ derived from millimeter measurements is similar to those of protoplanetary disks around T Tauri stars (Beckwith & Sargent 1991; Mannings & Emerson 1994; Andrews & Williams 2007) rather than that of the interstellar $\beta$ measured with the larger beams of the OVRO observations in Figure 1, and the filled ellipse in the bottom right corner in panel (c) shows the synthesized beam ($4′.3 \times 3′.4$; P.A. = $16′′$). The open circles show the field of view at the frequency of $^{13}$CO ($\sim 57′′$).

(A color version of this figure is available in the online journal.)

The integrated intensity maps of the $^{13}$CO ($J = 2–1$) line emission in L43 observed with the SMA. Each panel shows the integrated intensity map over (a) blueshifted (panels (j)–(l) in Figure 5), (b) systemic (panel (m)), and (c) redshifted (panels (n) and (o)) channels. The contour levels are from $3\sigma$ in steps of $2\sigma$, where the $1\sigma$ noise levels are $0.290$ mJy beam$^{-1}$ km s$^{-1}$, $0.167$ mJy beam$^{-1}$ km s$^{-1}$, and $0.237$ mJy beam$^{-1}$ km s$^{-1}$, respectively. The crosses indicate the peak position of the 225 GHz continuum emission in Figure 1, and the filled ellipse in the bottom right corner in panel (c) shows the synthesized beam ($4′.3 \times 3′.4$; P.A. = $16′′$). The open circles show the field of view at the frequency of $^{13}$CO ($\sim 57′′$).

4.2. Origin of Dust Continuum Emission

As was shown earlier, weak continuum emission was detected at the stellar position. The appearance of the emission is compact with some elongation, which could suggest that the emission arises from a compact circumstellar disk associated with the central star. The compactness of the emission, however, might be artificially created by our SMA observations resolving out extended structures. It is also noteworthy that typical Class 0 and Class I protostars are often associated with dust continuum emission arising from an envelope surrounding the protostar (e.g., Arce & Sargent 2006; Jørgensen et al. 2007).

In order to investigate whether the continuum emission arises from the innermost part of the extended envelope, we used a simple model of a spherical core to see whether we could reproduce the results obtained with SMA at 225 GHz. In the model, the intensity distribution of continuum emission at 225 GHz was assumed to be a power law, $I(r) \propto r^{-q}$. The power-law index, $q$, is estimated to be $1.1 \pm 0.39$ from the 450 $\mu$m data (Shirley et al. 2000). The total flux density of the continuum emission at 225 GHz within the core is estimated to be $274$ mJy by extrapolation from the far-infrared measurements at 450 $\mu$m and 850 $\mu$m (see the blue dashed line in Figure 2). To avoid divergence at $r = 0$, we assumed that the innermost part of the distribution has a hole where the intensity falls to zero. We tried various hole sizes from 50 AU to 800 AU in radius. With these models, observations using the actual SMA antenna configuration were simulated with the CASA Simulator.

The results of our simulated observations are summarized in Table 6 and Figure 10. For the model with a hole of 50 AU in radius, the expected flux density of 23.6 mJy is nearly twice...
Figure 7. Velocity channel maps of the C$^{18}$O ($J = 2–1$) line emission in L43 observed with the SMA. The contour levels are from $3\sigma$ in steps of $2\sigma$ ($1\sigma = 157\text{ mJy beam}^{-1}$). The central velocity of each channel is shown in the top left in units of km s$^{-1}$. The crosses indicate the peak position of the 225 GHz continuum emission in Figure 1, and the filled ellipse in the bottom right corner in panel (p) shows the synthesized beam ($4'.3 \times 3'.4; \text{P.A.} = 16'\circ$). The open circles show the field of view at the frequency of C$^{18}$O ($\sim 57.2$).

(A color version of this figure is available in the online journal.)

Table 6

| Radius (AU) | Hole     | Expected Flux (mJy) |
|------------|----------|---------------------|
| 50         | 37.9     | 41.4                |
| 100        | 30.3     | 38.1                |
| 200        | 19.1     | 30.0                |
| 400        | 8.6      | 19.4                |
| 800        | ... b    | ... b               |

**Notes.**

a Radius for an inner hole or a constant intensity region.

b Undetected.

as large as that of the actual observations. The expected flux density decreases as the radius of the hole becomes larger, and agrees with the observations when the radius is between 100 AU and 200 AU. Note that the central hole is marginally resolved in the resultant image with a hole of 200 AU in radius. Models with larger holes have smaller flux densities than the observations, and also show images with holes, which is inconsistent with the observed image.

We also tried models with constant intensities instead of null intensities within certain radii. As shown in Table 6, a model with a constant intensity within a given radius produces a larger flux density than the model with a hole having the same radius. In order for a model with a constant intensity to produce a flux density consistent with the observations, the radius for a constant intensity should be between 200 AU and 400 AU. These simulations suggest that the observations can be explained by assuming an envelope with a hole or a constant intensity region within a few hundred AU in radius.

Note that when the radius of a hole or a constant intensity region becomes more than 800 AU, emission from the envelope is undetectable with the present SMA observations. In such cases, the detected continuum emission can be still explained as that arising from a compact circumstellar disk associated with the central star.
The Astrophysical Journal, 789:95 (13pp), 2014 July 10

Koyamatsu et al.

Figure 8. (a) Integrated intensity map of the C$^{18}$O ($J = 2–1$) line emission (white contours), overlaid on the $K$-band image obtained with the Subaru Telescope (Mayama et al. 2007). The integrated $V_{LSR}$ range is indicated in the top right of the panel in units of km s$^{-1}$. The C$^{18}$O contour levels are from 3$\sigma$ in steps of 2$\sigma$ ($1\sigma = 0.254$ Jy beam$^{-1}$ km s$^{-1}$). The filled ellipse in the bottom right corner shows the synthesized beam (4$''$.4 $\times$ 3$''$.4; P.A. = 15$^\circ$). (b) $H - K$ color image obtained with the Subaru Telescope (Figure 2 in Mayama et al. 2007). P, L, G, and S are the names of components labeled in the reference.

Figure 9. Total integrated intensity map of the C$^{18}$O line in L43 obtained with the SMT. The integrated velocity range is from $-1.1$ km s$^{-1}$ to 1.9 km s$^{-1}$. The small crosses show the mapped points, and the large cross shows the protostellar position. The filled circle in the top left shows the SMT beam size ($\sim$34$''$.3). The contour levels are from 3$\sigma$ in steps of 3$\sigma$ ($1\sigma = 90$ mK km s$^{-1}$). The dashed circle indicates the region within 40$''$ from the protostar, where we calculate the LTE mass and virial mass of the protostellar envelope.

In the cases we discussed above, it is necessary for the innermost part of the envelope to have a hole or a constant intensity region. This suggests that the innermost envelope has less material than an ordinary envelope. The smaller amount of material in the innermost envelope around the L43 protostar is consistent with the results obtained from the comparison between C$^{18}$O map and the NIR scattering image in Section 3.2.3.

4.3. Disappearance of Protostellar Envelope

In the previous section, it was suggested that the innermost envelope around the L43 protostar seem to have a less amount of material. This may imply that the innermost envelope disappears for some reason. We now discuss this possibility in detail.

In the previous section, we used our results obtained with the SMA, which is sensitive to the innermost envelope, but is missing flux for larger-scale structures. In this section, we use single-dish data to determine the overall distributions of the envelope. In order to investigate the envelope distribution, the intensity distribution of continuum emission is examined here.

Shirley et al. (2000) observed 450 $\mu$m continuum emission around various Class 0/I protostars, including the L43 protostar, and fit the intensity distributions as a function of the distance from the protostars with power laws ($I_r \propto r^{-q}$). The power-law index for the envelope around the L43 protostar was estimated
to be $1.1 \pm 0.39$, as was explained in the previous section. As demonstrated in Figure 11, where the histogram of the power-law index of the intensity distributions for all the Class 0/I protostars observed by Shirley et al. is shown, the power-law index for the envelope around the L43 protostar is smaller than those for other protostars. This suggests that the envelope around the L43 protostar is less concentrated compared with those around other protostars. This lower concentration may be a result of the envelope’s disappearance.

Since the envelope seems to be disappearing, one may consider that it is no longer gravitationally bound. In order to investigate whether the envelope is gravitationally bound, we compare the H$_2$ gas mass within 40$''$ from the position of the central protostar, where dust continuum at 850 $\mu$m shows a clear condensation with the virial mass. The H$_2$ gas mass of the envelope is estimated to be $1.5 M_\odot$ for $T = 10$ K from the flux density at 850 $\mu$m using Equation (6), where $\kappa_\nu = 5.4 \times 10^{-3}$ cm$^2$ g$^{-1}$ at 850 $\mu$m with $\beta = 2.8$. On the other hand, the virial mass ($= M_{\text{vir}}$) is estimated from the line profile of C$^{18}$O $(J = 2\rightarrow1)$ emission obtained with SMT as follows.

$$M_{\text{vir}} = \frac{5DC_{\text{eff}}^2}{2G},$$  (7)

where $G$ is the gravitational constant, $D$ is the size of the object, $C_{\text{eff}}$ is the effective sound speed of gas as

$$C_{\text{eff}}^2 = \frac{\Delta V^2}{8 \ln 2},$$  (8)

where $\Delta V$ denotes the FWHM line width of the C$^{18}$O $(J = 2\rightarrow1)$ emission. We measure the FWHM line width of the C$^{18}$O profile in Figure 12 to be $\sim 0.59$ km s$^{-1}$ with a Gaussian fitting. The derived virial mass is $\sim 1.0 M_\odot$. Hence, if we take into account the central protostellar mass of $\sim 0.5 M_\odot$ (Levreault 1988), the envelope mass within 40$''$ is comparable with the virial mass, suggesting that the protostellar envelope around L43 is likely gravitationally bound.

![Figure 10](image1.png)

**Figure 10.** Examples of 225 GHz continuum maps obtained with our simulated observations. The radius of the hole or constant region is shown in the top right in each panel. The filled ellipse in the bottom right in panel (f) is the synthesized beam. The contour levels and the size of maps are the same as Figure 1.

![Figure 11](image2.png)

**Figure 11.** Histogram of the power-law index of the intensity distribution at 450 $\mu$m, $q$, in protostars (left axis) and its cumulative distribution (right axis). The measurements are taken from Shirley et al. (2000). The vertical dashed line indicates the value for L43 ($q = 1.1$).
At first glance, this result seems to be inconsistent with our idea that the envelope of L43 has been disappearing. However, we should note that the envelope can disappear when its material accretes onto the central star and the disk system. Since the protostar in L43 is still associated with a strong molecular outflow, it is naturally considered that the material in the envelope is still collecting onto the central star and disk system, and this process consumes the material in the envelope. We suggest that the envelope around L43 is disappearing through a process of accretion, at least in the close vicinity of the protostar.

5. SUMMARY

We present SMA data of L43, a transitional protostellar object from the Class I to T-Tauri stage, in the $^{12}$CO ($J = 2–1$), $^{13}$CO ($J = 2–1$), and $^{18}$CO ($J = 2–1$) emission lines, and the 225 GHz continuum emission, together with the new single-dish observations with the SMT in the $^{18}$CO ($J = 2–1$) line. The main results are summarized as follows.

1. The 225 GHz continuum emission shows a weak ($\sim 23.6 \pm 2.4$ mJy), compact (<1000 AU) component associated with the central star. Our simulated observations show the observed continuum emission can be explained by the dust thermal emission from the envelope, which has a hole or a constant intensity region within a few hundred AU of the central protostar. This suggests two possibilities: the disappearance of the envelope or a lower distribution of envelope material over a small-scale region. The dust opacity index $\beta$ ($\sim 0.46$) estimated from the millimeter interferometric observations is much smaller than the typical value of the interstellar medium ($\sim 1.7$) and low-mass protostellar sources ($\sim 1–1.7$), suggesting possible growth of dust grains.

2. The $^{12}$CO ($J = 2–1$) and $^{13}$CO ($J = 2–1$) emission exhibit blueshifted outflows toward the south of the central star, and redshifted outflows toward the north. The SMA observations resolve the innermost component of the blueshifted $U$-shaped outflow obtained with previous interferometric mosaicking observations. The direction of these small-scale outflow features, i.e., blueshifted toward the south and redshifted toward the north, is roughly consistent with the direction of the large-scale (>50,000 AU) outflow.

3. The SMA $^{18}$CO map shows two molecular blobs, which correspond to the reflection nebulosity seen in the near-infrared images. The dust extinctions at the positions of blobs (>10 mag) suggest that the origin of the $K$-band reflection is backward scattering at the blobs.

4. The envelope around the L43 protostar shows an intensity distribution with a power-law index of $1.1 \pm 0.39$, which is shallower than other protostars, suggesting a lower concentration of material in the envelope around the L43 protostar. The visible scattering features should result from the optical thinness of the envelope material in L43, which is consistent with the less-concentrated distribution in the continuum emission compared to other protostars. Such a low-concentration distribution of the envelope could be due to its disappearance. Because the mass of the envelope ($\sim 1.5 M_\odot$) + protostar ($\sim 0.5 M_\odot$) is comparable with the virial mass of $M_{\text{vir}} = 1.0 M_\odot$ within 40$^\prime\prime$ from the protostellar position, the protostellar envelope around L43 is likely gravitationally bound. We conclude that the protostellar envelope (at least in close proximity to the central protostar) is disappearing due to the consumption of envelope material through mass accretion onto the central star and disk system.

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