DENSE MOLECULAR CORES BEING EXTERNALLY HEATED

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ABSTRACT

We present results of our study of eight dense cores, previously classified as starless, using infrared (3–160 μm) imaging observations with the AKARI telescope and molecular line (HCN and N$_2$H$^+$) mapping observations with the KVN telescope. Combining our results with the archival IR to millimeter continuum data, we examined the starless nature of these eight cores. Two of the eight cores are found to harbor faint protostars having luminosities of $\sim$0.3–4.4 $L_\odot$. The other six cores are found to remain starless and probably are in a dynamically transitional state. The temperature maps produced using multi-wavelength images show an enhancement of about 3–6 K toward the outer boundary of these cores, suggesting that they are most likely being heated externally by nearby stars and/or interstellar radiation fields. Large virial parameters and an overdominance of red asymmetric line profiles over the cores may indicate that the cores are set into either an expansion or an oscillatory motion, probably due to the external heating. Most of the starless cores show a coreshine effect due to the scattering of light by the micron-sized dust grains. This may imply that the age of the cores is of the order of $\sim$10$^5$ years, which is consistent with the timescale required for the cores to evolve into an oscillatory stage due to external perturbation. Our observational results support the idea that the external feedback from nearby stars and/or interstellar radiation fields may play an important role in the dynamical evolution of the cores.

Key words: ISM: clouds – ISM: kinematics and dynamics – ISM: molecules – ISM: structure

1. INTRODUCTION

Starless cores are dense molecular regions of interstellar medium with densities of a few 10$^4$ cm$^{-3}$ and temperatures of $\sim$10 K where there are no embedded young stellar objects (YSOs) (e.g., Myers et al. 1983; Myers & Benson 1983; Ward-Thompson et al. 1994; Lee & Myers 1999; Bergin & Tafalla 2007). They are believed to be potential sites of future star formation (e.g., Lee & Myers 1999; Bergin & Tafalla 2007).

To have a better understanding of the star formation process, it is essential to have greater knowledge of how these cores form and evolve. According to the current understanding, the cores are thought to form basically in filamentary clouds and evolve as a result of fragmentation through gravitational instability when their masses exceed the critical mass per unit length. However, in reality, the details of how various processes such as ambipolar diffusion and turbulence dissipation work in the formation of such cores are still under debate (Shu et al. 1987; Ciolek & Mouschovias 1995; Myers & Lazarian 1998; Nakano 1998; André et al. 2014). Further, the final fate of the dense cores depends on the initial conditions set by the various physical environments in which they reside. Thus, the formation process of the dense cores may not be as simple as we think. However, it is certain that out of all the starless cores, the sufficiently dense ones have to undergo gravitational collapse to initiate star formation (e.g., Lee & Myers 2011).

In order to understand the current evolutionary status of starless cores, it is important to study their dynamical properties. One way of performing this is to carry out spectroscopic observations using molecular lines, which show asymmetry with self-absorption in the line profiles of optically thick species (e.g., CS 2-1, HCN 1-0) and Gaussian profiles in optically thin species (e.g., C$^{18}$O 1-0, N$_2$H$^+$ 1-0). In previous studies based on single pointing observations toward the central regions of starless cores, it was seen that approximately one-fourth of the starless cores show a double peak profile with blue asymmetry (the blue peak is higher in intensity than the red peak), indicative of inward motion (Walker et al. 1994; Lee et al. 1999, 2004; Sohn et al. 2007). However, of the remaining cores, a number of them displayed red asymmetry, which is the reverse of blue asymmetry, suggestive of expansion motion. In more extensive mapping observations that covered the entire projected area of the starless cores, roughly half of them showed dominance of blue asymmetric profiles over the whole mapped core area (Lee et al. 2001). This result suggests that these cores are undergoing gravitational infall and about to begin star formation. However, some of the remaining cores, which include B68 and FeSt 1-457, showed only red asymmetry or complex patterns of blue and red asymmetry, indicative of expansion or oscillation motions, respectively (Lee et al. 2001; Lada et al. 2003; Redman et al. 2006; Aguti et al. 2007). Moreover, these line profiles sometimes change their asymmetries according to the molecular line tracers in which the observations are made. This is because of the fact that different molecular lines or transitions have different optical depths and trace different regions of the dense cores (Gregersen et al. 1997).

Compiling the results from previous molecular line surveys, Lee & Myers (2011) made a statistical analysis to investigate the evolution of starless cores in various environments. Based on their study, they suggested that starless cores may evolve through a number of distinguishable evolutionary stages by
increasing their column density. To begin with, the cores evolve through a static stage which is then followed by an expanding and/or an oscillating stage. The star formation eventually occurs through the expanding and evolve through a static stage which is then followed by an increasing their column density. To begin with, the cores evolve through a static stage which is then followed by an expanding and/or an oscillating stage. The star formation eventually occurs through the expanding and eventua...
Object R.A.*,° Decl.*° Distance References b

| Object          | R.A.*  | Decl.* | Distance (pc) | References |
|-----------------|--------|--------|---------------|------------|
| CB22            | 04:40:39.9 | +29:52:59 | 140 ± 20 | 1          |
| L1517B          | 04:55:18.8 | +30:38:04 | 140 ± 20 | 1          |
| L1512           | 05:04:09.7 | +32:43:09 | 140 ± 20 | 1          |
| L1582A          | 05:32:03.4 | +12:31:05 | 400 ± 40 | 2          |
| L1621-1         | 05:55:59.4 | +02:18:02 | 500 ± 140 | 3          |
| L1041-2         | 20:37:17.8 | +57:49:21 | 440 ± 40 | 4          |
| L123A           | 23:17:57.6 | +62:26:39 | 300 ± 50 | 5          |
| CB246-2         | 23:56:49.2 | +58:34:29 | 140 ± 20 | 6          |

Notes.

- * The coordinates of targets are from Table 2 of Lee & Myers (1999).
- b The sensitivities of IRC and FIS are from Onaka et al.
- a The FWHMs of the IRC and the FIS are from Onaka et al.
- c Observing identification number ("OBSID") and dates of AKARI observations with IRC and FIS, respectively.

### Table 2

AKARI Observations for the Eight Dense Cores

| Object          | IRC Obs. Date | FIS Obs. Date |
|-----------------|---------------|---------------|
| CB22            | 2007 Mar 03   | 2007 Mar 03   |
| L1517B          | 2007 Mar 07   | 2007 Mar 07   |
| L1512           | 2007 Mar 08   | 2007 Mar 08   |
| L1582A          | 2007 Mar 14   | 2007 Mar 14   |
| L1621-1         | 2007 Mar 19   | 2007 Mar 19   |
| L1041-2         | 2006 Dec 14   | 2006 Dec 14   |
| L123A           | 2007 Jul 24   | 2007 Jul 24   |
| CB246-2         | 2007 Jan 23   | 2007 Jan 23   |

### Table 3

Specifications of AKARI Instruments

| Instrument | Wavelength (µm) | Bandwidth (µm) | FWHM* (") | Sensitivity (Soum) |
|------------|----------------|----------------|------------|--------------------|
| IRC        | 3              | 0.9            | 4.0        | 0.016              |
|            | 4              | 1.5            | 4.2        | 0.016              |
|            | 7              | 1.8            | 5.1        | 0.074              |
|            | 11             | 4.1            | 4.8        | 0.132              |
|            | 65             | 21.7           | 32.0       | 110                |
|            | 90             | 37.9           | 30.0       | 34.0               |
|            | 140            | 52.4           | 41.0       | 350.0              |
|            | 160            | 34.1           | 38.0       | 1350.0             |

Notes.

- The FWHMs of the IRC and the FIS are from Onaka et al. (2007) and Shirahata et al. (2009), respectively.
- The sensitivities of IRC and FIS are from Onaka et al. (2007) and Kawada et al. (2007), respectively.

### Table 4

Molecular Line Observations

| Object          | Mapping Size  | Sensitivity |
|-----------------|---------------|-------------|
|                 | HCN           | N₂H⁺        | \(\sigma_{\tau_{V,\text{HCN}}}[\text{K}]\) | \(\sigma_{\tau_{V,\text{N₂H⁺}}}[\text{K}]\) |
| CB22            | 330'' × 300'' | 240'' × 180'' | 0.09 | 0.10 |
| L1517B          | 180'' × 210'' | 150'' × 210'' | 0.12 | 0.14 |
| L1512           | 240'' × 270'' | 180'' × 210'' | 0.08 | 0.13 |
| L1582A          | 240'' × 180'' | 210'' × 120'' | 0.07 | 0.09 |
| L1621-1         | 60'' × 120''  | 60'' × 120''  | 0.09 | 0.08 |
| L1041-2         | 180'' × 240'' | 150'' × 240'' | 0.08 | 0.08 |
| L123A           | 120'' × 120'' | 90'' × 60''  | 0.06 | 0.06 |
| CB246-2         | 240'' × 270'' | 180'' × 150'' | 0.09 | 0.10 |

> 20070914, respectively. Observation parameters and the sensitivities of our AKARI observations are summarized in Table 3.

### 2.2. Molecular Line Observations

Although we selected our target cores based on the spectral line features, these features were identified based on the molecular line observations made toward the central regions of the cores only. Also, some of the observations lacked the signal-to-noise ratio (S/N) required to properly characterize the observed line shapes. Therefore, we carried out mapping observations for all our target sources in HCN (1-0) and N₂H⁺ (1-0) molecular lines with three 21-m radio telescopes of the Korean VLBI Network (KVN) located in Seoul (Yonsei site), Ulsan (Ulsan site), and Jeju island (Tamna site) of South Korea. The HCN (1-0) molecular line is known to be an optically thick tracer for gas motions in the density of \(\sim 10^7\) cm\(^{-3}\) and shows various asymmetry shapes in the three hyperfine lines with different relative opacities under the local thermal equilibrium condition (e.g., Sohn et al. 2007). The N₂H⁺ (1-0) molecular line is considered an optically thin tracer for the motion of gas in the densest region (\(\gtrsim 10^6\) cm\(^{-3}\)) of the core and consists of seven hyperfine lines (e.g., Tafalla et al. 2006).

These observations were carried out in a single dish observing mode between 2012 December and 2014 May. The data were obtained in a frequency switch mode with a frequency offset of 4 MHz with dual (left and right circular) polarizations. The two polarization profiles were averaged to get a single spectrum with a better S/N. As a back-end instrument, we used an autocorrelation spectrometer with a 32 MHz bandwidth and 7.825 kHz spectral resolution (corresponding to a velocity resolution of \(\sim 0.026\) km s\(^{-1}\) in the HCN line and \(\sim 0.025\) km s\(^{-1}\) in the N₂H⁺ line). The beam sizes (FWHM) and the main beam efficiencies of the three telescopes at Yonsei, Ulsan, and Tamna were \(32''\), \(33''\), and \(30''\), respectively.

The on-source integrated time for each position was typically between 15 and 30 minutes to achieve an S/N of \(\gtrsim 10\) in both HCN and N₂H⁺ lines at the central region of the cores, with a typical system temperature of 200−300 K at both frequencies during the observations. The pointing of the telescope was checked on an hourly basis using SiO maser sources located in the close vicinity of our target cores and found to be better than \(4''\). The data reduction, namely folding, baseline-subtracting, and averaging of the molecular line spectrum, was carried out using the CLASS software of the GILDAS package. Table 4 presents the observed sizes and sensitivities of the mapped regions of our target sources in both molecular lines.

Learn more about GILDAS at [www.iram.fr/IRAMFR/GILDAS](http://www.iram.fr/IRAMFR/GILDAS)
2.3. 2MASS, Spitzer, WISE, JCMT, and IRAM Data

Apart from our AKARI and molecular line observations, we also compiled multi-wavelength (IR to millimeter) images and photometric information for the eight cores from various data archives. The data from 2MASS, Spitzer, and WISE were obtained from the NASA/IPAC Infrared Science Archive.9 Because the 2MASS and the WISE missions were all-sky surveys, we obtained data at 1.2, 1.7, 2.2, 3.4, 4.6, 12, and 22 \( \mu m \) for all eight cores. However, Spitzer observations of the full extent of the cores at 3.6, 4.5, 5.8, 8.0, and 24 \( \mu m \) are available only for CB22, L1512, and L1517B. L1582A and L1041-2 were observed partially by Spitzer at the same wavelengths mentioned above. CB246-2 was observed at 3.6, 4.5, 5.8, and 8.0 \( \mu m \), but not at 24 \( \mu m \). The Spitzer and the WISE missions had an overlap in their wavelength coverages. In situations where the data from both these facilities were available, we preferred to use those from Spitzer because of its better angular resolution and sensitivity compared to the WISE. For 22 \( \mu m \) data, we used the data from the WISE mission.

The continuum data at millimeter or sub-millimeter regimes are very important in order to better constrain the physical properties of dense cores and embedded sources. However, the data in these wavelength regimes are available only for five out of eight sources in either data archives or previous publications. We obtained 850 \( \mu m \) data for three of our cores, namely CB246-2, L1512 (fully observed), and L1517B (partially observed) from the JCMT science archive.10 We also used continuum 1200 \( \mu m \) data for L1041-2 and L1582A from Kauffmann et al. (2008). Table 1 summarizes the availability of continuum data for our target cores.

2.4. Photometry

Even though all the cores selected by us were classified previously as starless, some of them were found to contain faint point sources. In order to study them in detail and discern their true nature, we performed aperture photometry on these detected point sources. The aperture photometry was made using the IDL11 routine “aper.pro,” particularly for the point sources detected at wavelengths longer than 20 \( \mu m \) as we were interested in only those sources that are embedded and currently forming inside the core. The point sources were

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9 http://irsa.ipac.caltech.edu/

10 http://www.cadc.hia.nrc.gc.ca/jcmt/search/product/

11 http://www.exelisvis.com/ProductsServices/IDL.aspx
extracted in cases where the signal was about $3\sigma$ above the background noise at 22, 24, or 65 $\mu$m. The positions of the point sources were obtained from the 3.6 $\mu$m images. Using the IDL routine, gcntrd.pro, we computed the coordinates of the point sources by performing Gaussian fits to their emission distribution. The photometry was carried out on all the sources detected in images of all the wavelengths except for those from 2MASS and WISE bands. The photometric results in 2MASS and WISE bands are already available in the point source catalogs (Cutri et al. 2003; Cutri et al. 2012). The results from our photometry were compared with those from the 2MASS and WISE databases. The results were found to be in good agreement within the uncertainty. The aperture radius and the sky annulus (inner radius and width) used for the aperture photometry were set to be different at different wavelengths in order to avoid any contamination from the neighboring sources.

In the IRC02 mode of AKARI, the observations in the 3 and 4 $\mu$m were obtained with two exposures of 44.4 and 4.7 s, respectively. The long exposure observations were made to detect the faint sources while the short-exposure observations were made to avoid the saturation of the bright sources in the frame. The AKARI images with long exposures sometimes showed artifacts like muxstripe, muxbleed, and column pulldown basically due to the presence of a bright point source. For sources affected by these artifacts, we used the short-exposure image for the photometry. The measured flux density from the point sources was converted into the physical unit “Jansky” by applying the conversion factor and the aperture correction factor for each band (Engelbracht et al. 2007; Hora et al. 2008; Tanabé et al. 2008; Shirahata et al. 2009).

3. RESULTS AND DISCUSSIONS

3.1. Multi-wavelength Images of Eight Dense Cores

The AKARI images of the eight cores studied here are presented in Figure 1. Images of the cores in other wavelengths, obtained from the archives, are also presented in the same figure, which is ordered according to increasing wavelength. Starting with the optical images in the top left panel and ending with the 1200 $\mu$m in the bottom right panel, the central wavelength corresponding to each of the images is labeled in the top left corner. A contour on each of the panels is a half minimum contour level of the extinction region in the optical image, indicating the approximate boundary of a dense core. The presence of dense cores is conspicuous in all the optical images as dark opaque patches. The cores appear dark because the submicron-sized solid particles present in them extinguish the light coming from the background stars. However, because of less extinction suffered in near-infrared wavelengths, the light from the background stars can penetrate through the opaque regions of the dense cores. This makes the cores transparent in the wavelength range of $\sim$1.2 ~$\sim$4.5 $\mu$m. As a result, numerous background point sources are visible.

Figure 1. (Continued.)
through the cores. Some of these sources could be embedded protostars. It is interesting to note that six of the eight dense cores in our sample show some scattered diffuse emission at 3.0–4.5 μm wavelength range. This is thought to be due to the “coreshine effect” (Pagani et al. 2010). More discussion on this is presented in Section 3.3.2.

The number of point sources seen toward the dense cores is drastically reduced between 5.8 and 11 μm and the scattered light due to the coreshine effect also appears to diminish. Instead, at these wavelengths, the background becomes bright with diffuse emission and the dense cores appear dark. This effect gets more prominent at 11 μm. This is believed to be due to the emission coming from the polycyclic aromatic hydrocarbons (PAHs) situated along the Galactic plane in the background (Tielens 2008). The PAH emission features peak at 7.6 and 11.3 μm and thus are slightly shifted from the central wavelengths of the IRC bands. However, the IRC bands at 7 and 11 μm are wide enough (1.8 and 4.1 μm, respectively; Onaka et al. 2007) to include some of the strong PAH emission features and hence collect emission originating from them. Most of the cores in our sample are seen in absorption with respect to the bright PAH background emission.

Point sources visible at 22–65 μm are believed to be good candidates of embedded YSOs (e.g., Robitaille et al. 2006, 2007; Whitney et al. 2013). While no point sources with characteristic properties of YSOs are detected within the observed fields of AKARI toward six of our target cores, a few YSO candidates are found in two of them, namely L1582A and L1041-2. Figures 1(d) and (f) show that there are eight possible YSO candidates in L1582A and two in L1041-2. The heating of the surrounding dust by the radiation from these embedded YSOs is believed to be the main reason for the higher brightness at 90, 140, and 160 μm. Other dense cores (CB22, L1517B, L1512, L1621-1, L1234, and CB246-2) also show some emission at these wavelengths, particularly near the boundaries of the cores, even though there is no evidence of any heating source within them. We believe that such emission is caused by external heating of the cores. Properties of the detected YSO candidates and their effects on the parent cores are discussed in detail in the next section. The effects of external heating on the starless cores in our sample are discussed further in Section 3.3.

3.2. Newly Detected Sources Embedded in “Starless” Dense Cores

We found a number of point sources, likely to be embedded, in two of the dense cores that were previously classified as starless by Lee & Myers (1999). The detected point sources are believed to be protostars because of their higher brightnesses at 22–65 μm than at the shorter wavelengths (e.g., Robitaille et al. 2006, 2007; Whitney et al. 2013). In this section we derive their bolometric temperatures ($T_{bol}$) and bolometric
luminosities ($L_{bol}$) and explore whether or not they are associated with the cores.

### 3.2.1. Bolometric Temperatures and Luminosities of the Point Sources

The $T_{bol}$ and $L_{bol}$ are useful quantities for investigating the physical properties of YSOs (e.g., Myers & Ladd 1993; Chen et al. 1995). These quantities can be estimated from the SEDs of the sources (e.g., Myers & Ladd 1993; Evans et al. 2009). The $T_{bol}$ is defined as the temperature of a blackbody having the same mean frequency $\nu$ as the observed continuum spectrum (Myers & Ladd 1993) and can be derived by the equation:

$$T_{bol} = \left[ \frac{\zeta(4)}{4\zeta(5)} \right] \frac{h\nu}{k} = 1.25 \times 10^{-11} \nu \text{ KHz}^{-1},$$  
(1)

where $\zeta(n)$ is the Riemann zeta function of the argument $n$, $h$ is Planck’s constant, and $k$ is Boltzmann’s constant (Myers & Ladd 1993). Here the mean frequency $\bar{\nu}$ is obtained from the ratio of the first and the zeroth frequency moments of the spectrum (Ladd et al. 1991):

$$\bar{\nu} = \frac{\int_0^\infty \nu S_\nu d\nu}{\int_0^\infty S_\nu d\nu}.$$  
(2)

On the basis of the calculated $T_{bol}$ values, point sources can be classified into five evolutionary groups (e.g., Evans et al. 2009):

- $T_{bol} < 70$ K: Class 0
- $70$ K $\leq T_{bol} < 350$ K: Class I
- $350$ K $\leq T_{bol} < 950$ K: Flat spectrum
- $950$ K $\leq T_{bol} < 2800$ K: Class II
- $2800$ K $< T_{bol}$: Class III

The $L_{bol}$, the total energy emitted by the point source per unit time, is calculated by integrating the flux over the full observed SED, assuming that the source has a spherical geometry (Chen et al. 1995):

$$L_{bol} = 4\pi D^2 \int_0^\infty S_\nu d\nu,$$  
(3)

where $D$ is the distance from the observer to the core and $S_\nu$ is the flux density at the specific frequency. We derived $T_{bol}$ and $L_{bol}$ for all the point sources detected in L1582A and L1041-2. A good coverage of their SEDs from 1.2 $\mu$m to 1.2 mm (as shown in Figure 2) enabled us to estimate $T_{bol}$ and $L_{bol}$ quite accurately. Based on the values of $T_{bol}$, we found that all of them are likely to be either protostars of Class 0 or I or flat-spectrum sources. Their luminosities are found to be in the range $0.3 \sim 4.4 L_\odot$. The derived bolometric temperature, bolometric luminosity, classification, and the flux densities of...
these protostellar candidates are summarized in Table 5. We note that the values of $L_{\text{bol}}$ that are obtained in this work could be significantly affected by the uncertainty due to the unknown geometry of the Class I and flat-spectrum sources. Because of the difficulty in determining the geometry of these sources due to the lack of knowledge of parameters such as the inclination of the disk and the cavity, the opening angle of the cavity, and so on, we ignored this uncertainty. Therefore, the uncertainty of $L_{\text{bol}}$ quoted by us was obtained by simply propagating the errors of the distance and the flux densities in Equation (3). The uncertainty of the values of $T_{\text{bol}}$ was also obtained by propagating the errors of the flux densities. The errors due to the aperture photometry are the main source of uncertainty in the measurements of the flux densities.

### 3.2.2. Association of Point Sources with Dense Cores

It is important to ascertain whether the YSO candidates identified by us in L1582A and L1041-2 are actually associated with them or not. It could be possible that they are simply a chance projection along the line of sight and not physically related to the cores at all. However, if they are related, then their presence could modify some of the properties of the cores such as the temperature structure and the kinematics of the material surrounding them.

Using the photometric data at 90, 140, 160, 850, and 1200 μm, we created the temperature maps of all the cores studied here. The available data for each of the dense cores are listed in Table 1. We first subtracted the sky background intensity by selecting an emission-free region close to our target cores, re-gridded to the same pixel scales (15″), and convolved to a 41″ beam that corresponds to the lowest angular resolution among the 90–1200 μm images to look for any variation in the temperature in the vicinity of the identified YSO. The temperature corresponding to each set of pixels was estimated by fitting the flux densities obtained in those pixels at 90–1200 μm with the modified blackbody function given by

$$S_{\nu}(\nu) = \frac{1}{\Omega}(1 - e^{-\tau(\nu)})B_{\nu}(\nu, T_d) - I_{\text{bg}}(\nu)$$  \hspace{1cm} (4)$$

with

$$\tau(\nu) = N_{\text{H}} \kappa_{\text{d}}(\nu, T_d),$$  \hspace{1cm} (5)$$

where $S_{\nu}(\nu)$ is the flux density at frequency $\nu$, $\Omega$ is the solid angle, $\tau(\nu)$ is the optical depth, $B_{\nu}(\nu, T_d)$ is the Planck function, $T_d$ is the dust temperature, $I_{\text{bg}}$ is the background intensity, $N_{\text{H}} = 2 \times N(\text{H}_2) + N(\text{H})$ is the total hydrogen column density, $m_{\text{H}}$ is the hydrogen mass, $M_d/M_{\text{H}}$ is the dust-to-hydrogen mass ratio, and $\kappa_{\text{d}}(\nu)$ is the dust mass absorption coefficient (e.g., Nielbock et al. 2012; Launhardt et al. 2013).
In Equation (5), $\kappa_d(\nu)$ is obtained from the tabulated values given by Ossenkopf & Henning (1994) for mildly coagulated composite dust grains with thin ice mantles called “OH5.”

Although $I_{bg}$ is dominated by the cosmic background radiation and the diffuse Galactic background, we did not consider them separately since our sky subtraction procedure also would remove their contributions. Equation (4) for various values of temperature is fitted to the observed fluxes of each set of pixels. The temperature corresponding to the fit with the lowest $\chi^2$ value is considered the temperature of the corresponding pixels. Five of the eight dense cores have data at wavelengths (either 850 or 1200 $\mu$m) beyond the expected peaks of their SEDs. For this reason we could produce temperature maps quite reliably for L1517B, L1512, L1582A, L1041-2, and CB246-2. However, the remaining three dense cores lack continuum data at these longer wavelengths. Therefore, our estimated value of the temperature is considered an upper limit. Despite this, the temperature maps produced without using longer wavelengths are still useful to examine the presence of any spatial temperature variation in them. Our temperature maps for the cores with embedded sources are shown in Figure 3.

We also made two sets of color-composite (CC) images for all eight cores. The first one is made using 7, 22, and 65 $\mu$m images. All but IRS 3a/b are located along the southern and western edges of the core. The brightest of them, L1582A-IRS6, is identified with a known pre-main sequence star, V453 Ori (Dolan & Mathieu 2001). Our $L_{bol}$ estimation is quite consistent with the value calculated by Cohen & Kuhi (1979). There are a number of Herbig–Haro sources detected in the vicinity of V453 Ori and L1582A-IRS5, suggesting that the region is an active site of current star formation (Magakian et al. 2004). The CC image at 65, 90, and 160 $\mu$m of L1582A shows enhanced emission at the longer wavelength of 160 $\mu$m at the locations of the YSO candidates identified in L1582A, its color being red. This implies that the YSO sources in L1582A are surrounded by dust envelopes that are not heated as high as...
about 50 K but instead remain cold. The temperature map for L1582A does not show any clear local temperature enhancement at the location of most YSOs except for L1582A-IRS4 and IRS7. This may indicate that either the YSOs are not luminous enough to heat the entire dense cores or the expected local heating of their immediate environments is most likely smoothed out by the large beam (41″) of observations. One noticeable feature seen in L1582A is that the temperature is found to be enhanced along the southern and western edges of the core. The warm southwestern boundary may actually indicate local heating by L1582A-IRS4 and 7, which seem less embedded than the other YSOs such as L1582A-IRS2 and 3. These two YSOs may thus heat the dense core from this side. There may be another possibility for the local heating in the southwestern edge of L1582A. L1582A is a part of the bright-rimmed cloud, Barnard 30, and its southern edge is pointing roughly toward the λ Ori cluster (Collinder 69) which includes the O8III+B0V binary λ OriAB (Duerr et al. 1982; Zhou et al. 1988; Zhang et al. 1989; Lang et al. 2000). It is possible that L1582A, located ~20 pc away from the central star λ Ori, is heated externally, causing the temperature toward the southern and western edges to rise. At the moment, it is not clear which of the two effects dominates. From CC images and temperature maps, it is not certain that the most detected YSO candidates are physically related to L1582A.

In L1041-2, we detected two possible YSO candidates, IRS1 and IRS2, which could be embedded in the core. The CC image with 65, 90, and 160 μm shows red color around two YSO candidates, implying that they are also surrounded with cold envelopes like the case of L1582A. However, at the location of L1041-2-IRS2, which is located just outside the boundaries of the dense core, the CC map also shows a local bluish spot, and the corresponding temperature map displays more clearly a local temperature enhancement, again indicating that this YSO is less embedded and the heating of its immediate surroundings can therefore be detected. However, there is no obvious local enhancement in the temperature around L1041-2-IRS1. This may be similar to the cases of most YSOs in L1582A. Moreover, enhancement in the temperature is seen toward the eastern and northeastern parts of the core; this enhancement is thought to be due to the external heating by the interstellar radiation field. In L1041-2, using CC maps and temperature maps, it also seems to be difficult to determine the physical association between YSOs and their parent clouds.

However, it is still generally acceptable to suggest that the YSOs are physically associated with their parent cores L1582A and L1041-2 simply from the spatial correlation between the YSOs and the high extinction of the dense core, which would probably prohibit seeing a background source, and the statistical improbability of a by-chance alignment of the YSOs and the cores (L1582A and L1041-2).
Investigation of the kinematic structure of the dense cores is another way to ascertain the physical association of the YSO candidates with them. For this reason, we made mapping observations of the dense cores using N$_2$H$^+$ (1-0) to look for any line broadening around the envelopes due to star-forming activities. We obtained line widths of N$_2$H$^+$ (1-0) by making seven hyperfine Gaussian fits to the lines. The (D) panels of Figure 3 show the variation of line width in contours around the candidate protostars in L1582A and L1041-2. We noticed that the line widths are significantly broadened around the locations of the YSO candidates in L1582A (IRS 3a/b) by a factor of $\sim$1.5 and in L1041-2 (IRS1 and IRS2) by a factor of $\sim$1.6 $-$ 2.2 when compared with the line widths of the other positions in the cores. We also made mapping observations of the cores using the HCN (1-0) line to look for any evidence of infall asymmetry in these cores. Figure 4 shows the line profile maps of the main component ($F = 2$-1) among three HCN hyperfine lines superposed with the half-maximum contour of the N$_2$H$^+$ integrated intensity. Note that most of them show a blue asymmetry in double peaks where the blue peak is brighter than the red peak, indicative of inward motions of gas in the dense core. The kinematic signatures obtained above also suggest that the YSO candidates detected in these cores are most likely associated with the cores.

3.3. “Starless” Dense Cores

3.3.1. External Heating of the Starless Cores and Its Effects

In the previous section we found that two of the eight dense cores, formerly classified as starless based on the non-existence of IRAS point sources (Lee & Myers 1999), are now identified as small clouds with multiple embedded (protostellar) cores. However, the other six dense cores in our sample are still starless. Here we discuss their physical status and possible future evolution by using continuum and line emission data.

Like the two protostellar cores discussed in the previous section, we present CC images and temperature maps for six starless cores in Figure 5. In the CC images at 7, 22, and 65 $\mu$m, the absence of any bright point source at 22 and/or 65 $\mu$m indicates that these dense cores are indeed starless. We found that the brightness of our starless cores tends to be more centrally concentrated at longer wavelengths. L1517B, L1512, and CB246-2 show high brightness toward their central regions at either 850 or 1200 $\mu$m as shown in Figure 1, implying that they are centrally more condensed with cold gas and dust material. However, we could not examine the cloud structure of the other three starless cores, CB22, L1621-1, and L1234, due to the lack of data toward longer wavelengths. In contrast, all six cores were observed and detected with strong emission at 90, 140, and 160 $\mu$m. Particularly, the cores CB246-2 and
L1517B show bright emission toward the central region at both 140 and 160 $\mu$m. This implies that their dust emission is concentrated more toward the central region as manifested in both 140 and 160 $\mu$m and in 850 or 1200 $\mu$m wavelength regimes. However, the emission pattern seen in the other four starless cores, namely CB22, L1512, L1621-1, and L1234 is somewhat different. In these four cores, the emission from 90 to 160 $\mu$m is brighter toward the outer regions of the cores where the dust column density is relatively lower compared with that toward the central regions. Notably, the temperature maps produced for these cores (Figure 5) show an increase of 3–6 K toward the outer parts of the cores when compared with the central regions. One interesting feature seen in the wavelength range from 90 to 160 $\mu$m in six of the eight cores is the asymmetric emission (and also temperature) pattern enhanced toward a particular portion of the outer rim of the cores. This effect has been noticed in other dense cores as well, for example, B68 (Nielbock et al. 2012), CB130 (with 11 dense cores, Launhardt et al. 2013), L1155, and L1148 (Nutter et al. 2009).

Heating by the isotropic interstellar radiation field (ISRF) and/or nearby stars was considered the possible reason for the observed asymmetric rim heating. Nutter et al. (2009) carried out the radiative transfer modeling of a dense core having a Plummer-like sphere with both the isotropic ISRF and directional nearby stellar radiation field, showing that the increase (3–6 K) in the temperature toward the boundaries of the core can be reproduced by the mean ISRF and the asymmetric emission feature could be produced by the presence of any nearby exciting star(s) at IR wavelength bands. We believe that while the mean ISRF alone may cause an observable increase in the temperature toward the outer parts

Figure 2. Spectral energy distributions for possible YSOs found in the dense cores L1582A and L1041-2. In the bolometric luminosity calculation, we assumed that the distances of protostars are the same as those of the parent cores (400 pc for L1582A and 440 pc for L1041-2).
| Object               | Coordinates          | \( L_{\text{bol}}^a \)  | \( T_{\text{bol}}^b \) | Classification | \( 1.24 \mu \text{m} \) | \( 1.66 \mu \text{m} \) | \( 2.16 \mu \text{m} \) | \( 3.0 \mu \text{m} \) | \( 3.6 \mu \text{m} \) | \( 4.0 \mu \text{m} \) |
|---------------------|----------------------|--------------------------|--------------------------|-----------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| L1582A-IRS1         | 05:32:12 +12:29:42.0 | 1.6 ± 0.5                | 63 ± 20                  | 0                | 0.31 ± 0.02         | 0.73 ± 0.06         | 1.9 ± 0.2           | 1.5 ± 0.1           | 2.4 ± 0.1           | 3.0 ± 0.1           |
|                     |                      |                          |                          |                 | 3.6 ± 0.2           | 4.1 ± 0.2           | 9.6 ± 1.1           | 7.4 ± 0.3           | 14 ± 1              | 290 ± 65            |
|                     |                      |                          |                          |                 | ...                 | 1132 ± 46           | 1899 ± 54           | 13501 ± 321         | 10300 ± 200         | 110 ± 3             |
| L1582A-IRS2         | 05:32:08 +12:30:34.6 | 2.8 ± 0.8                | 97 ± 26                  | I               | 0.32 ± 0.03         | 1.6 ± 0.1           | 6.0 ± 0.5           | 18 ± 1              | 23 ± 1              | 43 ± 1              |
|                     |                      |                          |                          |                 | 40 ± 1              | 50 ± 1              | 66 ± 2              | 48 ± 1              | 48 ± 2              | 245 ± 55            |
|                     |                      |                          |                          |                 | ...                 | 2561 ± 67           | 4361 ± 80           | 18244 ± 373         | 18174 ± 266         | 479 ± 7             |
| L1582A-IRS3a        | 05:32:03 +12:31:17.4 | 1.2 ± 0.2                | 124 ± 21                 | I               | 0.32 ± 0.02         | 3.1 ± 0.2           | 8.2 ± 0.6           | 16 ± 2              | 13 ± 1              | 15 ± 1              |
|                     |                      |                          |                          |                 | 13 ± 1              | 12 ± 1              | 15 ± 1              | 12 ± 1              | 14 ± 1              | 160 ± 3             |
|                     |                      |                          |                          |                 | 80 ± 3              | 739 ± 26            | 1410 ± 33           | 7320 ± 167          | 11280 ± 148         | 299 ± 4             |
|                     |                      |                          |                          | Flat             | 0.97 ± 0.07         | 14 ± 1              | 57 ± 4              | 94 ± 1              | 138 ± 1             | 127 ± 1             |
|                     |                      |                          |                          |                 | 142 ± 1             | 122 ± 1             | 118 ± 2             | 101 ± 1             | 120 ± 2             | 311 ± 70            |
|                     |                      |                          |                          |                 | 272 ± 5             | 865 ± 28            | 1676 ± 35           | 8270 ± 178          | 11280 ± 148         | 335 ± 4             |
| L1582A-IRS4         | 05:31:54 +12:31:33.4 | 0.9 ± 0.3                | 71 ± 26                  | I               | 0.52 ± 0.04         | 1.4 ± 0.1           | 2.4 ± 0.2           | 4.2 ± 0.1           | 1.8 ± 0.1           | 3.4 ± 0.1           |
|                     |                      |                          |                          |                 | 2.4 ± 0.1           | 2.9 ± 0.2           | 4.8 ± 0.6           | 4.5 ± 0.2           | 4.0 ± 0.7           | 28 ± 6              |
|                     |                      |                          |                          |                 | 36 ± 3              | 739 ± 26            | 1528 ± 34           | 8019 ± 175          | 6150 ± 109          | 1583 ± 3            |
| L1582A-IRS5         | 05:31:50 +12:31:26.1 | 2.3 ± 0.8                | 300 ± 97                 | I               | 21 ± 2              | 46 ± 4              | 47 ± 4              | 30 ± 1              | 25 ± 1              | 18 ± 1              |
|                     |                      |                          |                          |                 | 16 ± 1              | 11 ± 1              | 17 ± 2              | 8 ± 1               | 18 ± 2              | 16 ± 4              |
|                     |                      |                          |                          |                 | 19 ± 2              | 1606 ± 54           | 2596 ± 63           | 18640 ± 3771        | 15641 ± 247         | 111 ± 3             |
| L1582A-IRS6         | 05:31:49 +12:31:58.3 | 4.4 ± 1.3                | 453 ± 122                | Flat             | 74 ± 6              | 104 ± 8             | 115 ± 9             | 123 ± 1             | 156 ± 2             | 106 ± 1             |
|                     |                      |                          |                          |                 | 121 ± 1             | 94 ± 1              | 89 ± 2              | 170 ± 1             | 152 ± 2             | 140 ± 31            |
|                     |                      |                          |                          |                 | 171 ± 6             | 2473 ± 66           | 5718 ± 91           | 25461 ± 441         | 26257 ± 320         | 119 ± 3             |
| L1582A-IRS7         | 05:31:54+12:30:42.5  | 1.6 ± 1.4                | 45 ± 39                  | 0                | 0.06 ± 0.04         | ...                 | 0.13 ± 0.06         | 0.76 ± 0.17         | 0.11 ± 0.03         | 0.66 ± 0.08         |
|                     |                      |                          |                          |                 | 0.04 ± 0.02         | 0.60 ± 0.08         | 19 ± 1              | 1.5 ± 0.1           | 20 ± 2              | 28 ± 6              |
|                     |                      |                          |                          |                 | 53 ± 3              | 2113 ± 61           | 3346 ± 71           | 12882 ± 314         | 7804 ± 174          | 259 ± 5             |
| L1041-2-IRS1        | 20:37:19 +57:49:07.6  | 0.6 ± 0.5                | 27 ± 21                  | 0                | ...                 | 0.08 ± 0.05         | 0.03 ± 0.06         | 0.07 ± 0.01         | 0.05 ± 0.02         | 0.11 ± 0.01         |
|                     |                      |                          |                          |                 | 0.06 ± 0.02         | 0.04 ± 0.02         | 0.16 ± 0.03         | 0.22 ± 0.04         | 0.39 ± 0.04         | 0.87 ± 0.30         |
|                     |                      |                          |                          |                 | 0.72 ± 0.25         | ...                 | ...                 | 1432 ± 88           | 2368 ± 82           | 112 ± 3             |
| L1041-2-IRS2        | 20:37:12 +57:47:49.8  | 0.3 ± 0.1                | 220 ± 109                | I                | 0.14 ± 0.01         | 0.09 ± 0.01         | 1.2 ± 0.1           | 3.9 ± 0.1           | 6.5 ± 0.2           | 8.4 ± 0.1           |
|                     |                      |                          |                          |                 | 9.8 ± 0.3           | 14 ± 0.3            | 13 ± 1              | 17 ± 1              | 19 ± 1              | 58 ± 21             |
|                     |                      |                          |                          |                 | 54 ± 3              | 47 ± 10             | 72 ± 12             | 538 ± 64            | 1421 ± 74           | 679 ± 8             |

Notes.

\(^a\) The uncertainties of \( L_{\text{bol}} \) were estimated by propagating the errors of distance and flux densities.

\(^b\) The uncertainties of \( T_{\text{bol}} \) were calculated by propagating the errors of flux densities.

\(^c\) The uncertainties of flux densities are the errors resulting from performing the aperture photometry for the sources.
of the cores, the presence of nearby single or multiple stars, in addition to the ISRF heating, as a second order effect, may cause heating of the sides of the cores that are facing the star(s).

In order to examine this further, we made a search for any potential source or sources around the six cores that could externally heat and hence enhance the temperature toward the boundaries. The search was conducted by visually inspecting the nearby stars whose spectral type and distance are known from the Simbad astronomical database and the Hipparcos catalog (Nesterov et al. 1995; van Leeuwen 2007). In at least three of the six cores, namely CB22, L1517B, and L1512, we found potential candidates that are situated within an angular separation of 1° and toward the side where we noticed the enhancement in the temperature in the cores. These heating sources are found to be of spectral types A or F and are 0.2–0.7 pc away in projected distance from the dense cores. For the remaining three cores (L1234, L1621-1, and CB246-2) we could not find any potential star whose distance is known in the vicinity. However, in the case of L1234, we find that a very bright IRAS point source is located 2/2 away from it and to the side where the maximum heating in the core is noticed. From the SED of the IRAS source, we found that this object is a Class II YSO and bright enough (L_{bol} ~ 47 L_{⊙}) to heat the southern part of L1234, provided that it is located at a distance similar to that of the core.

In the case of L1621-1, an increase in the temperature is noticeable to the northern part of the core. Interestingly, a similar increase in the temperature (toward the northern part) is also visible in another core located to the south of L1621-1. This provides convincing evidence for the existence of a possible exciting source to the north of L1621-1. We searched for potential candidates in the northern direction of L1621-1 and found several sources such as HD 39952 (A3 type) and a number of IRAS sources. In CB246-2, the temperature map shows an enhancement all around the boundary of the core, implying that multiple sources situated around it may be responsible for the observed temperature profile. We found a number of potential candidates from A to F type stars within a 10 arcminute angular distance of CB246-2. More information on the potential exciting candidates found toward L1621-1 and CB246-2 is required to confidently determine the source or sources responsible for the external heating of these cores. In Table 6, we list all the potential sources that could possibly heat the respective cores externally along with their properties such as spectral type, distance, and luminosity.
as spectral type, distance, and projected distance from the core. In Figure 6 (1° × 1° DSS optical images) we show their spatial locations with respect to the cores. The cores are delineated using a half-minimum contour of optical extinction regions in yellow. The curve in red indicates the direction of the core where the envelopes show a relative enhancement in temperature.

Another way to diagnose whether a core has been subjected to any external effect is to look for an asymmetric shape in a molecular line profile toward the cores. Lada et al. (2003), Redman et al. (2006), and Aguti et al. (2007) have shown that any disturbance to the core by an external pressure, possibly due to, for instance, nearby OB stars, can create oscillatory motions in the cores. This could produce a spatially complex pattern of red and blue asymmetry line profiles over the dense core depending on the oscillation mode of the core. In Figure 7 we show profile maps of \( F = 2-1 \) components of HCN (1-0) lines overlaid on the half-maximum contour of the integrated intensity of N\(_2\)H\(^+\) (1-0) lines for our six starless cores. Four of the starless cores, namely L1512, L1517B, L1621-1, and CB246-2, display the dominance of “red” asymmetry line profiles, i.e., double peaks where the blue peak is fainter than the red peak. CB22 is found to consist of two N\(_2\)H\(^+\) sub-cores. While its northern sub-core shows a dominance of blue asymmetric profiles over the entire half-maximum contour of N\(_2\)H\(^+\) integrated intensity, the southern core exhibits a mixture of blue and red profiles. This result shows that the two sub-cores have different kinematic statuses. The northern sub-core is in overall inward motion, whereas the southern sub-core is experiencing a complex oscillatory motion. In the case of L1234, its kinematic behavior is unclear because although the HCN line appears asymmetric, its peak velocity coincides with that of N\(_2\)H\(^+\). To summarize, the kinematics inferred from HCN (1-0) line profiles for all the starless cores, except for L1234, is surprisingly consistent with what is expected from perturbation by external heating of the dense cores. Such oscillation motions can cause the cores to increase their central density to change their dynamical status to contracting motions (Stahler & Yen 2009). Therefore, we believe that these cores are under external perturbation and may be in dynamically unstable statuses, either in a combination of expansion and contraction modes or in an expansion-dominant mode.

An alternative way to diagnose whether the cores are affected by external heating and their stability is consistent with the overabundance of “red” asymmetric line profiles toward the cores is to conduct a virial analysis. In order to do this, we need to derive the virial and core masses. By ignoring the effects of external pressure, magnetic field, and rotation, the virial mass...
of a core is given by

\[
M_{\text{vir}} = \frac{5}{8 \ln 2} \frac{R \Delta v_m^2}{\alpha \beta G},
\]

where \( R \) is the radius of a dense core, \( \Delta v_m \) is the FWHM of the line profile of a gas with a mean molecular mass, \( G \) is the gravitational constant, and \( \alpha \) is the geometric factor for eccentricity. The value of \( \beta \) is the correction factor for a non-uniform density distribution \( (\beta = (1-p/3)/(1-2p/5)) \), where \( p \) is the power-law index of the density profile \( (\rho \propto r^{-p}, 0 \leq p \leq 2) \) (e.g., McKee & Zweibel 1992; Caselli et al. 2002a; Chen et al. 2007; Miettinen 2012). The \( \Delta v_m \) is obtained from the molecular line observation here in \( \text{N}_2\text{H}^+ \) by

\[
\Delta v_m^2 = \Delta v_T^2 + \Delta v_{NT}^2
\]

\[
= \Delta v_{\text{obs}}^2 + 8 \ln \frac{k T_k}{m_{\text{H}} \mu} \left( \frac{1}{\mu} - \frac{1}{\mu_{\text{obs}}} \right),
\]

where \( \Delta v_T \) is the thermal line width, \( \Delta v_{NT} \) is the non-thermal line width, \( \Delta v_{\text{obs}} \) is the FWHM of the observed molecular line, \( k \) is the Boltzmann constant, \( T_k \) is the kinetic temperature, \( m_{\text{H}} \) is the mass of the hydrogen atom, \( \mu \) is the mean particle weight (\( = 2.33 \text{ amu} \)), and \( \mu_{\text{obs}} \) is the mass of the observed molecule.

Figure 5. (a) Same as Figure 3 but the color-composite and temperature maps for three starless cores, CB22, L1517B, and L1512. (b) Same as Figure 3 but the color-composite and temperature maps for three starless cores, L1621-1, L1234, and CB246-2.
In the calculation of the virial mass of our six starless cores, we simply assume that the cores are uniform spherical spheres ($\alpha = 1, p = 0$) with a kinetic temperature of 10 K (e.g., Benson & Myers 1989; Caselli et al. 2002a). The observed line width $\Delta v_{\text{obs}}$ is obtained with an average of the FWHM line widths for the N$_2$H$^+$ line profiles within the half-maximum contour of N$_2$H$^+$ intensity distribution.

The core mass can be calculated by using a simple equation $M = \mu_H m_H N_{H_2} \Omega_A$, where $\mu_H$ is the mean molecular weight per hydrogen molecule ($\mu_H = 2.8$; Kauffmann et al. 2008), $m_H$ is the mass of a hydrogen atom, $N_{H_2}$ is the column density of hydrogen molecules, $\Omega_A$ is the area of a dense core. The area ($\Omega_A$) enclosed within the half-maximum of the integrated intensity of the N$_2$H$^+$ (1-0) molecular line is considered in the calculation. Because the dense cores are not ideally spherical, we define an effective radius ($r = \sqrt{\Omega_A / \pi}$) of the area as the dense core radius ($R$). The column density ($N_{H_2}$) can be calculated by using the Equation (A4) of Caselli et al. (2002b).

To get the column density, we need to measure the integrated intensity ($I$) and the excitation temperature ($T_{\text{ex}}$) from molecular line data. The integrated intensity is given by integrating over a velocity range of seven hyperfine line components. The excitation temperature ($T_{\text{ex}}$) can be obtained.
Notes.

a The distance of the source was derived using the Hipparcos parallax measurements obtained from van Leeuwen (2007). The distance of IRAS 23158+6208 was assumed to be the same as that of the parent core.

b The spectral types of the stars are from Nesterov et al. (1995).

c The radii and bolometric temperatures of the stars were obtained from Cox (2000). For IRAS 23158+6208, the bolometric temperature was estimated from its spectral energy distribution.

d The bolometric luminosity was derived from the bolometric temperature and the radius of the star. For IRAS 23158+6208, the bolometric luminosity was estimated from the spectral energy distribution of the source.

e The projected distance between the star and the core was calculated by assuming that the star and the core have the same distance from us.

by fitting hyperfine structures of the N$_2$H$^+$ (1-0) line into its seven components. So the mass of a dense core can finally be derived from the column density of H$_2$ by adopting the abundance of X(N$_2$H$^+$) $\sim$ 6.8 (±4.8) x 10$^{-10}$ as derived by Lee & Myers (2011) for 35 starless cores from the table provided by Johnstone et al. (2010). The masses of the cores estimated based on the N$_2$H$^+$ line intensity are given in column 7 of Table 7.

In some cases the abundance of the N$_2$H$^+$ molecule can be chemically affected depending on the environments where the cores exist and thus the masses of the cores using N$_2$H$^+$ line observations can be highly uncertain. Therefore we also derived the core masses ($M_{\ast}$) using 2MASS extinction maps as another mass measurement. From the extinction maps produced based on the 2MASS star counts (Dobashi 2011), we measure the total extinction value (in magnitude) within the half-maximum contour of the N$_2$H$^+$ intensity map and then convert it to the H$_2$ column density of the core by using the relation of N(H$_2$)/A$_V$ = 9.4 x 10$^{20}$ cm$^{-2}$ mag$^{-1}$ (Bohlin et al. 1978). The calculated masses of the cores are given in column 8 of Table 7. We compare the masses based on the N$_2$H$^+$ line and those using the 2MASS extinction. Both estimates of the core masses are found to be consistent within the calculation uncertainties.

For all the cores in our sample, we estimated the ratio between the virial mass and the core mass which is defined as $\alpha = 2K/W = M_{vir}/M_{obs}$, where $K$ is the internal kinetic energy of a dense core, $W$ is the gravitational energy, and $M_{vir}$ and $M_{obs}$ are the virial and the core mass, respectively (e.g., Bertoldi & McKee 1992; McKee & Zweibel 1992; Kauffmann et al. 2013). On the basis of the value of $\alpha$, we can diagnose the dynamical instability of a dense core. The $\alpha > 1$ or $\alpha < 1$ may mean that the dense core would either expand or collapse, respectively. The $\alpha \approx 1$ may mean that the dense core would be under stable conditions and in virial equilibrium. Observed and virial masses for all six starless cores including their related quantities are listed in Table 7. Interestingly enough, although the masses have large uncertainties, all the cores have a virial parameter ($\alpha$) larger than unity. There are many uncertain factors in the mass estimation for the virial parameters. We discuss these to ascertain the significance level of the virial values estimated by us.

The uncertainties in the factors such as the distances of the cores and the measurements of the molecular line widths may cause the virial mass estimation quite uncertain. However, among these, the uncertainty caused due to our assumption of a constant density distribution for the cores is thought to be the dominant one. For example, if the cores have a power-law density distribution, instead of having a constant density distribution ($p = 0$) as assumed here, the virial mass would decrease by $\sim$40%. The uncertainties of the virial masses given in Table 7 are those estimated by propagating the errors of the parameters in Equation (6).

The uncertainty in N$_2$H$^+$ abundance contributes more to the uncertainty of the core mass estimated using the N$_2$H$^+$ data than the errors introduced due to the uncertainty in the measurement of the integrated intensity and the distance of the cores. One of the major factors that makes the estimation of the abundance uncertain is the chemical differentiation of the N$_2$H$^+$ (e.g., Busquet et al. 2010). The value of abundance adopted by us could make the core mass estimation uncertain by a factor of 1.4.

The core mass estimated using the 2MASS extinction maps, $M_{A_V}$, can also be uncertain due to a number of factors such as the noise error in the extinction values and the uncertainty in the distance to the core. In addition to this, the $M_{A_V}$ values can also be systematically underestimated since the high column density regions of the dense cores can be selectively missed due to the possible lack of stars toward these regions. We tested this possibility by estimating the masses based on the $A_V$ values from the 2MASS extinction maps of the dense cores for which the masses have already been estimated using 1.2 mm continuum data (Kauffmann et al. 2008). The core masses estimated based on the $A_V$ values from the 2MASS extinction maps are found to be underestimated by about 40% which is considered to be the dominant error in the estimation of $M_{A_V}$ values.

In this manner we derive all possible uncertainties in the mass estimation and in the final virial parameters for the cores by propagating the errors. The virial parameters for all the starless cores are found to be significantly larger than unity.
considering their uncertainties. This implies that all six cores are, most likely, either expanding or are confined by the external pressure.

In summary, the far-IR emission and temperature enhancement in the boundary of the dense cores, the overdominance of asymmetric “red” profiles in the HCN line over the cores, and the virial parameters larger than unity of the cores are all consistent with the suggestion that our dense starless cores are externally heated and have unstable statuses, i.e., they are either expanding or confined by the external pressure.

Figure 6. DSS optical images of $1^\circ \times 1^\circ$ for the starless cores CB22, L1517B, L1512, L1621-1, L1234, and CB246-2 and nearby heating sources. The yellow contour displays the approximate boundary of each dense core, which is the half-minimum contour level of its extinction region in the optical image. The curves in red indicate the direction toward which the envelopes show a relative enhancement in temperature. The arrow in white is to indicate possible heating objects for which the spectral type and the distance are known from Nesterov et al. (1995) and van Leeuwen (2007).
3.3.2. Coreshine Effects in Dense Cores and Its Implication

A coreshine effect, first reported by Pagani et al. (2010) with an analogy to the cloud shine discovered in large clouds by Mathis et al. (1977) and Foster & Goodman (2006), occurs when the central parts of dense cores appear bright due to the scattered light from micron-sized dust grains that are buried deep inside the cores. This is shown with a contrasting feature between the scattered emission at 3 and 4 \( \mu \)m and the absorption at 7 and 11 \( \mu \)m and is better identified when no embedded source exists inside the cores to radiate at near-

Figure 7. (a) Same as Figure 4 but of three starless cores, CB22, L1517B, and L1512. The right panel displays the average spectra over the half-maximum contour of the N$_2$H$^+$ integrated intensity. The minimum level, maximum level, and interval of the N$_2$H$^+$ integrated intensity are as follows: CB22, 0.24, 2.39, 1.19 K km s$^{-1}$; L1517B, 0.32, 3.17, 1.59 K km s$^{-1}$; L1512, 0.41, 4.06, 2.03 K km s$^{-1}$. (b) Same as Figure 4 but of three starless cores, L1621-1, L1234, and CB246-2. The right panel displays the average spectra over the half-maximum contour of the N$_2$H$^+$ integrated intensity. The minimum level, maximum level, and interval of the N$_2$H$^+$ integrated intensity are as follows: L1621-1, 0.07, 0.68, 0.34 K km s$^{-1}$; L1234, 0.1, 1.0, 0.48 K km s$^{-1}$; CB246-2: 0.26, 2.57, 1.29 K km s$^{-1}$.
Figure 7. (Continued.)
Table 7
Observed and Virial Masses and Related Quantities of the Six Starless Cores

| Object  | $V_{lsr}$(N$_2$H$^+$) (km s$^{-1}$) | $ΔV$(N$_2$H$^+$) (km s$^{-1}$) | $T_{ex}$ (K) | $R_{obs}$ (pc) | $N$(H$_2$)$_{peak}$ ($×10^{12}$ cm$^{-2}$) | $M_{obs}$ ($M_\odot$) | $M_ν$ ($M_\odot$) | $M_\ast$ ($M_\odot$) | $α_{vir}$ |
|---------|-------------------------------|-------------------------------|--------------|---------------|---------------------------------|-----------------|----------------|----------------|----------|
| CB22N   | 5.96 ± 0.01                   | 0.23 ± 0.02                   | 16 ± 2       | 0.04          | 4.3 ± 3.1                       | 0.52 ± 0.38     | 0.33 +0.14    | 0.33 +0.05    | 3.0 ± 0.19 |
| CB22S   | 5.96 ± 0.01                   | 0.21 ± 0.02                   | 24 ± 3       | 0.03          | 5.2 ± 3.7                       | 0.41 ± 0.30     | 0.11 +0.05    | 0.11 +0.02    | 3.5 +0.16  |
| L1517B  | 5.81 ± 0.01                   | 0.21 ± 0.02                   | 6 ± 1        | 0.04          | 7.4 ± 5.3                       | 0.72 ± 0.52     | 0.76 +0.13    | 2.0 +0.06    | 2.9 +0.09  |
| L1512   | 7.07 ± 0.01                   | 0.19 ± 0.01                   | 15 ± 1       | 0.04          | 8.9 ± 6.3                       | 0.76 ± 0.56     | 0.28 +0.12    | 1.6 +0.07    | 2.2 +0.18  |
| L1621-1 | 1.78 ± 0.01                   | 0.15 ± 0.01                   | 12 ± 1       | 0.07          | 2.8 ± 2.0                       | 0.98 ± 0.76     | 1.26 +0.49    | 3.0 +0.32    | 3.1 +0.29  |
| L1234   | −5.05 ± 0.02                  | 0.32 ± 0.05                   | 4 ± 1        | 0.04          | 3.8 ± 2.7                       | 0.33 ± 0.24     | 0.89 +0.19    | 2.5 +0.18    | 7.8 +0.68  |
| CB246-2 | −0.82 ± 0.02                  | 0.26 ± 0.02                   | 5 ± 1        | 0.04          | 6.0 ± 4.3                       | 0.56 ± 0.41     | 0.53 +0.08    | 2.0 +0.09    | 3.7 +0.31  |

**Note.** Column (1): source name. Column (2): average LSR velocity (derived from seven hyperfine Gaussian fits to the N$_2$H$^+$ lines) of the spectra within the half-maximum (HM) contour of the N$_2$H$^+$ intensity map. Column (3): average line width (derived from seven hyperfine Gaussian fits to the N$_2$H$^+$ lines) of the spectra within the HM contour of the N$_2$H$^+$ intensity map. Column (4): average excitation temperature (derived from seven hyperfine Gaussian fits to the N$_2$H$^+$ lines) for the spectra within the HM contour of the N$_2$H$^+$ intensity map. Column (5): effective radius of an area enclosing the HM contour of the N$_2$H$^+$ intensity map. Column (6): column density of H$_2$ toward the N$_2$H$^+$ (1-0) intensity peak position. Column (7): H$_2$ mass (derived from N$_2$H$^+$ (1-0) data) of the core within the HM contour of its N$_2$H$^+$ intensity map. Column (8): H$_2$ mass (derived from the 2MASS extinction data) of the core within the HM contour of its N$_2$H$^+$ intensity map. Column (9): virial mass for the core within the HM contour of its N$_2$H$^+$ intensity map. Column (10): virial parameter $α = M_\ast/M_{obs}$.

Figure 8. Flux density ratio ($f(3 \, \mu m)$ and $f(7 \, \mu m)$) and cut profiles (at 3 $\mu$m and 7 $\mu$m intensity maps) of L1517B as an example of the coreshine effect.
calculations of the grain coagulation from the typical grain-size distribution in the interstellar medium by Hirashita & Li (2013) have shown that it would take at least several free-fall times (a few $10^7$ years) to form micrometer-sized dust grains in a number density of $10^{10} \text{cm}^{-3}$. Therefore, the dense cores showing the coreshine effect may not be dynamically transient, but are likely to be long-lived objects. The lifetime inferred from the coreshine effect is consistent with the lifetime inferred from the dynamical statuses of our starless cores. Lee & Myers (2011) have shown that starless cores in different internal motions may reflect different stages of evolution in terms of the increasing column density. In the previous section we found that our starless cores are likely to be in expanding and/or oscillating modes according to their HCN spectral shapes and large virial parameters. Then their age, if they are in a dynamical status, is suggested to be $\sim 3 \times 10^5$ years (Lee & Myers 2011) which is interestingly comparable to the coagulation time of micron-sized grain that produces the coreshine effect in the cores.

We note that four starless cores (CB22, L1517B, L1512, and CB246-2) in our sample have higher column densities (listed in column 6 of Table 7) than the critical ones ($\sim 6 \times 10^{21} \text{cm}^{-2}$) over which the cores are likely to be contracting (Lee & Myers 2011). We believe that these four cores are most likely to be on the verge of collapse to initiate star formation.

4. CONCLUSIONS

We present results of our imaging observations of eight previously classified starless dense cores using the AKARI telescope. Using the KVN telescope, we also carried out mapping observations of these cores in HCN and $\text{N}_2\text{H}^+$ lines. Combining our results with those from the data obtained from other space- and ground-based facilities in multi-wavelength (near-IR to millimeter), we re-examined the starless nature of these cores. Of the eight cores studied here, two of them, L1582A and L1041-2, were found to harbor point sources showing properties of YSOs. The luminosities of these YSO candidates are in the range from 0.3 to 4.4 $L_\odot$. The absence of any embedded source in the remaining six cores confirmed their starless nature. The temperature maps produced for these six starless cores using multi-wavelength continuum images show enhancements of about 3–6 K toward the outer boundaries which suggests that these cores are being heated externally. We found a few potential A–F type stars and/or interstellar radiation fields in the vicinity of some of these cores which could be responsible for heating the cores externally. The optically thick HCN (1-0) line profiles in five of the six starless cores (CB22S, L1517B, L1512, L1621-1, and CB246-2) show a dominant red asymmetry over their projected areas. This indicates that the cores are perturbed due to external radiation and are set into an expansion or oscillatory motion. The results from the virial analysis also are found to be consistent with an expansion or oscillatory status.

Five of the starless cores studied here show evidence of a coreshine effect along with temperature enhancement toward the outer boundary and red profiles in their molecular maps. Considering that the coreshine effect is produced due to the scattering of radiation by micron-sized dust grains present deep inside the cores, the ages of the cores (of the order of $10^5$ years) inferred from the coagulation time of the grains is found to be consistent with the timescale required for the cores to attain an oscillatory stage of evolution. This suggests that these cores are not transient but are long-lived dense cores. Four out of these five cores (CB22, L1517B, L1512, and CB246-2) are found to have column densities higher than the critical ones ($\sim 6 \times 10^{21} \text{cm}^{-2}$) and may be close to the collapse stage from which stars can form. Our observational results altogether suggest that the external feedback by nearby stars and/or interstellar radiation fields may play a significant role in the dynamical evolution of the cores.

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