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| **Author(s)** | Nishimura, Atsushi |
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Observational Study of the Physical Properties of Giant Molecular Clouds by the 1.85-m Millimeter/Sub-millimeter Telescope

Atsushi Nishimura

Osaka Prefecture University

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Abstract

This thesis is devoted to observational studies of the physical properties of molecular clouds for the better understanding of the star formation process. The cloud properties (e.g., mass, density, temperature) are expected to trace the evolutionary phases of molecular clouds, and thus to reflect the characteristics of the star formation activities. In addition, the properties are also expected to probe the effect of the interaction from the surrounding environment which is supposed to determine the modes of star formation. Hence the investigation of the physical properties of molecular clouds is a key to the understandings of star formation. However, there have been only a small amount of studies with the spatially resolved observations of the clouds properties mainly due to the absence of the appropriate instruments. Therefore, we developed a new millimeter/sub-millimeter radio telescope which is optimized for the large scale surveys of the physical properties of the molecular clouds. In this thesis, We describe the detailed information of the developed telescope and the observational results of a survey toward the Orion molecular clouds.

The telescope is designed to conduct multi-line observations of CO rotational transitions toward nearby molecular clouds. The target frequency is 230 GHz band; simultaneous observations in the $J=2-1$ rotational lines of carbon monoxide isotopes ($^{12}$CO, $^{13}$CO, C$^{18}$O) are achieved with a beam size (FWHM) of 2.7. In order to accomplish the simultaneous observations, we developed waveguide-type sideband-separating SIS mixers to obtain spectra separately in the upper and lower side bands. A Fourier digital spectrometer with a 1 GHz bandwidth with 16384 channels is installed and the bandwidth of each spectrometer is divided into three parts, each of which corresponds to each spectrum, and the IF system has been designed so as to inject these three lines into the spectrometer. A flexible observation system was created mainly in python on Linux PCs, enabling the effective on-the-fly scan mapping for the large area mapping. The telescope is enclosed in a radome with a membrane covered to prevent a harmful effect of the sunlight, strong wind, and precipitation, minimizing the error in the telescope pointing and stabilizing the receiver and the IF
devices. The telescope was installed at the Nobeyama Radio Observatory, and we started the science operations from 2011 January.

Using the 1.85-m telescope, we carried out multi-line CO ($J=2–1$ of $^{12}$CO, $^{13}$CO, C$^{18}$O) observations toward the entire area of the Orion A and B giant molecular clouds. The data were compared with the $J=1–0$ of the $^{12}$CO, $^{13}$CO, and C$^{18}$O data taken with the Nagoya 4-m telescope and the NANTEN telescope at the same angular resolution to derive the spatial distributions of the physical properties of the molecular gas. We explore the large velocity gradient formalism to determine the gas density and temperature by using the line combinations of $^{12}$CO($J=2–1$), $^{13}$CO($J=2–1$), and $^{13}$CO($J=1–0$) assuming uniform velocity gradient and abundance ratio of CO. The derived gas temperature is mostly in the range of 20 to 50 K along the cloud ridge with a temperature gradient depending on the distance from the star forming region. We found the high-temperature region at the cloud edge facing to the H$_{II}$ region, indicating that the molecular gas is interacting with the stellar wind and radiation from the massive stars. The derived gas density is in the range of 500 to 5000 cm$^{-3}$. The high density regions ($\gtrsim$ 2000 cm$^{-3}$) are located toward the cloud edge facing to the H$_{II}$ region, suggesting the compression of the molecular gas by the stellar wind and radiation. In addition, we compared the derived gas properties with the distributions of Young Stellar Objects obtained with the Spitzer telescope to investigate the relationship between the gas properties and the star formation activity therein. We found that the gas density and star formation efficiency are well positively correlated, indicating that stars form effectively in the dense gas region.

The results indicate that the combination of a optically thick line (e.g., $^{12}$CO $J=2–1$) and different transitions of optically thin lines (e.g., $^{13}$CO $J=2–1$, $^{13}$CO $J=1–0$) are important to derive the precise cloud properties. The future study of the similar analyses toward the other molecular clouds which have different environment as well as different mode/stage of the star formation would advance our understanding about the mechanism of star formation.
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Chapter 1

Introduction

Stars are the most fundamental components of the universe. They affect the evolution of galaxies by generating energy and producing heavy elements. Characteristics of stars are essentially decided by the initial mass, determining the luminosity, size, evolution, lifespan, and eventual fate. In other words, the fate of stars are sealed at the moment of its formation. Therefore, the understanding of the process of the star formation is one of the most essential issues in the astronomy.

In this thesis, I investigate the physical properties of molecular clouds, which are the formation sites of stars, with a newly developed millimeter/sub-millimeter wave telescope. Here we introduce the observed characteristics of the molecular clouds.

1.1 Molecular Clouds

According to the modern cosmology, the total energy of the universe contains 4.9% ordinary matter, 26.8% dark matter, and 68.3% dark energy. Nine tenths of ordinary matter is present as fixed stars, and the rest is present in the interstellar medium (ISM). The ISM consists of gas, dust, and cosmic rays. About 99% of the ISM is gas, and 1% is dust by mass. The ISM is classified according to its phase, which is distinguished by whether the matter is ionic, atomic, or molecular, and the temperature and density of the matter (Table 1.1). The molecular clouds are the phase that the density is the highest, the temperature is the lowest, and most of the gas is existed in the molecular state. The molecular clouds account for less than 1% of the ISM by volume.

The main constituent of the molecular clouds is molecular hydrogen. However, the H$_2$ has no emission at the low temperature of the molecular clouds, and thus the
rotational lines of the other molecules are often used as tracers of the amount of the molecular gas by assuming its relative abundance to the H$_2$. Since the critical density and absorption coefficient differ by molecules and transitions, each tracer has the specific condition to have the emission. This means each tracer probes the different region in the molecular clouds. Therefore, the hierarchical structure of the density of the molecular clouds can be investigated by multi-line observations using tracers with the different critical densities or optical depth (Figure 1.1). For example, the $J$=1–0 transition line of the $^{12}$C$^{16}$O (hereafter $^{12}$CO) is widely used as a tracer of the total amount of the molecular clouds because of its small critical density and its very large optical depth, allowing it to excite in the molecular gas whose density is higher than several hundred cm$^{-3}$. In other instances, the optically thin lines such as $^{13}$C$^{16}$O and $^{12}$C$^{18}$O (hereafter $^{13}$CO, and C$^{18}$O, respectively) and the lines with the higher critical density such as CS and H$^{13}$CO$^+$ are used as dense gas tracers.

1.1.1 Hierarchical Density and Size Structures of Molecular Clouds

Extensive surveys of the molecular clouds had been carried out after the discovery of the line emission of the $^{12}$CO($J$=1–0) (Wilson et al. 1970). The Columbia survey is the widest $^{12}$CO($J$=1–0) survey along the Galactic plane by using two 1.2-m millimeter wave telescope (Dame & Thaddeus 1985; Solomon et al. 1987; Dame et al. 1987, 2001). The NANTEN 4-m telescope also conducted an extensive survey of the $^{12}$CO($J$=1–0) with the improved angular resolution of 2.7 arcmin (e.g., Kawamura et al. 1999; Tachihara et al. 2001; Mizuno et al. 2001; Yamamoto et al. 2006). These early CO surveys revealed the large-scale distribution of the molecular clouds. Recently, the FCRAO 14-m telescope was enhanced with multi-beam array receiver and they surveyed some of giant molecular clouds (GMC) with an angular resolution of
about 40 arcsec (Jackson et al. 2006; Goldsmith et al. 2008; Ripple et al. 2013).

The emission line of $^{13}$CO($J=1-0$) is used as a probe of the inner structure of the molecular clouds because of its small optical depth. The early $^{13}$CO surveys revealed the filamentary and clumpy nature compared with the rather featureless structure of the $^{12}$CO distributions (e.g., Bally et al. 1987). The 4-m millimeter wave telescope at the Nagoya University conducted extensive surveys in the $^{13}$CO($J=1–0$) (Dobashi et al. 1994, 1996; Mizuno et al. 1995; Yonekura et al. 1997; Nagahama et al. 1998; Kawamura et al. 1998). They identified the embedded structures as $^{13}$CO clouds or $^{13}$CO filaments, and discussed the dynamic state, mass spectrum, and relation to the YSO distributions. The $^{13}$CO clouds have typically masses of $>100 M_\odot$, sizes of several tens of pc, column densities of $\sim 10^{21}$ cm$^{-2}$, and mass spectrum indices of $\sim 1.6$, and they are gravitationally unbounded without the external pressure.

The emission line of $^{18}$O is surveyed toward the region where $^{12}$CO or $^{13}$CO is intense. The $^{18}$O($J=1–0$) is widely surveyed with the Nagoya University 4-m telescope (Onishi et al. 1996, 1998; Tachihara et al. 2000; Aoyama et al. 2001; Yonekura et al. 2005). They identified the $^{18}$O cores with the same method as the $^{13}$CO clouds. The $^{18}$O cores have typically, masses of several $M_\odot$, sizes of a few sub-pc, column densities of $\sim 10^{22}$ cm$^{-2}$, densities of $>10^3$ cm$^{-3}$, and mass spectrum indices of $\sim 2$ or smaller, and they are often gravitationally bounded.

The higher density tracers such as CS are often used to investigate the dense cores in higher angular resolutions taken with the larger telescope such as the Nobeyama 45-m telescope. The large scale surveys of the CS were conducted, for example, toward Orion molecular clouds (Lada et al. 1991; Tatematsu et al. 1993, 1998). They identified the dense cores, which have sizes of $\sim 0.1$ pc, densities is $10^4$–$10^5$ cm$^{-3}$, and the indices of core mass function (CMF) of $\sim 1.6$. However, it is known that molecular depletion seems to be sometimes serious for CO and CS in starless, cold molecular cloud cores (e.g., Caselli et al. 1999; Aikawa et al. 2001). Therefore, the H$^{13}$CO$^+$ and N$_2$H$^+$ are used to probe the dense gas these days (Aoyama et al. 2001; Onishi et al. 2002; Ikeda et al. 2007, 2009; Tatematsu et al. 2008). The properties of the dense cores identified in H$^{13}$CO$^+$ are basically similar to that of CS, except for their CMF indices of $\sim 2.5$ which resembles the stellar initial mass function (IMF). This fact indicates the problem of the IMF would comes down to the problem of the CMF determining with higher density tracer gas.
Figure 1.1: Maps of the molecular gas in the Cygnus OB7 complex in different map sizes with different angular resolutions. The indicated linear sizes are given for a distance to Cygnus OB7 of 750 pc. From Falgarone et al. (1992).
1.1.2 Filamentary Structures of Molecular Clouds

The filamentary structures are ubiquitously found in molecular clouds in rotational lines of CO (e.g., Bally et al. 1987; Mizuno et al. 1995; Nagahama et al. 1998; Goldsmith et al. 2008; Schneider et al. 2011), and in images at mid-infrared wavelengths as ”infrared dark clouds” (IRDCs) (e.g., Gutermuth et al. 2008; Butler & Tan 2009), and at dust emission (e.g., André et al. 2010; Peretto et al. 2012; Hill et al. 2012; Kirk et al. 2013; Rivera-Ingraham et al. 2013; Harvey et al. 2013; Polychroni et al. 2013). For example, Figure 1.2 shows an image of the dust emission toward the California giant molecular cloud taken with Herschel Space Observatory (Harvey et al. 2013). The prevalence of the filamentary structure suggests that it may persist for a large fraction of a typical cloud lifetime. Therefore, such structures may provide clues to the star formation process, especially for the origin and geometry of star-forming dense cores. For instance, recent observations of Herschel Space Observatory show that the most of pre-stellar cores are associated with the filamentary structures (Polychroni et al. 2013). However, the origin of the filamentary structure is a subject of controversy. The understandings of the evolution process of the molecular clouds, especially the enhancement mechanism of the density are important for the filament formations and thus the star formation therein.

Figure 1.2: False color image with 70 μm (blue), 160 μm (green), and 250 μm (red) of the mapping observation results toward the California giant molecular cloud taken by Herschel Space Observatory. From Harvey et al. (2013).
1.1.3 Environmental Effects

It is also known that star formation appears to have two main modes, spontaneous and triggered. Spontaneous star formation is the predicted result of the gravitational collapse under the naturally turbulent molecular-cloud environment (for a review, Mac Low & Klessen 2004). This mode is expected to produce a background of the star formation efficiency (SFE) and then, the star formation ratio (SFR). On the other hand, triggered star formation increases the SFE and SFR due to the effects of interactions to molecular cloud gas, usually caused by the stellar winds, radiation or expanding HII regions associated with massive stars (e.g., Elmegreen & Lada 1977; Elmegreen 1998; Deharveng et al. 2005). There are two main mechanisms to increase the SFE locally. The first is by creating new star-forming structures which is described as the collect-and-collapse mechanism (Elmegreen & Lada 1977). In the mechanism, the flows of winds or thermal expansion driven with massive stars create fragments which are located between the ionized front and shocked front, and it becomes to form dense cores due to its gravitational instability. The second is by collapsing the pre-existing dense cores to form stars. In the mechanism, the ambient pressure is increased by the passage of a shock wave or an ionization front.

These modes would have the big impact to determine the SFE and formation process of the filaments and then, star forming cores. The observations of the enhancement of the density and temperature are of crucial importance to investigate the environmental effects of the clouds.

1.1.4 Observations of Physical Properties

The gas kinetic temperature, $T_{\text{kin}}$, and gas density, $n(\text{H}_2)$, are the important properties of the molecular clouds for the study of the star formation. However, usually these properties can’t be observed directly. In this subsection, we briefly summarize the techniques to derive the gas properties.

Basic Concept

Observed line intensity, $T_{\text{mb}}$, is given by the radiative transfer equation:

$$ T_{\text{mb}} = \frac{h\nu}{k} \left[ \frac{1}{\exp\left(\frac{h\nu}{kT_{\text{ex}}}) - 1 \right)} - \exp\left(\frac{h\nu}{kT_{\text{bg}}}) - 1 \right)} \right) (1 - e^{-\tau}), $$

(1.1)
where $\nu$ is the observed frequency, $T_{\text{ex}}$ is the excitation temperature, $T_{\text{bg}}$ is the cosmic background temperature of 2.725 K, and $\tau$ is the optical depth. The excitation temperature states the excitation condition of the line, which is defined by,

$$\frac{n_{J+1}}{n_J} = \frac{g_{J+1}}{g_J} \exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right),$$  \hspace{1cm} (1.2)

where $n_J$ and $g_J$ are the population and statistical weight for the energy level $J$, respectively.

The statistical equilibrium equation of an arbitrary volume in the molecular clouds is defined by, for simplicity, in the two level formula:

$$n_J(B_{J,J+1}I_\nu + C_{J,J+1}) = n_{J+1}(A_{J+1,J} + B_{J+1,J}I_\nu + C_{J+1,J}),$$  \hspace{1cm} (1.3)

where $A$ and $B$ are Einstein’s coefficient for spontaneous emission and photo absorption/induced emission, respectively. The $C$ is a collision coefficient described by,

$$C_{J+1,J} = n(H_2)\gamma_{J+1,J},$$  \hspace{1cm} (1.4)

where $\gamma_{J+1,J}$ is a mean free path defined by $\sigma_{J+1,J}\langle v \rangle$, $\sigma_{J+1,J}$ is a collision cross-section, and $\langle v \rangle$ is a mean velocity. In these coefficients, following relations hold:

$$A_{J+1,J} = \frac{2h\nu^3}{c^2}B_{J+1,J}$$  \hspace{1cm} (1.5)

$$\frac{B_{J+1,J}}{B_{J,J+1}} = \frac{g_J}{g_{J+1}}$$  \hspace{1cm} (1.6)

$$g_J\gamma_{J,J+1} = g_{J+1}\gamma_{J+1,J}\exp\left(-\frac{h\nu}{kT_{\text{kin}}}\right),$$  \hspace{1cm} (1.7)

The radiation intensity at the arbitrary volume $I_\nu$ is derived by assuming the escape probability of the emitted photon $\beta_\nu$ and neglects the $T_{\text{bg}}$, then,

$$I_\nu = (1 - \beta_\nu)B_\nu(T_{\text{ex}}),$$  \hspace{1cm} (1.8)

where $B_\nu$ is a Planck function. From (1.2)–(1.8), the $T_{\text{ex}}$ is derived by,

$$T_{\text{ex}} = \frac{T_{\text{kin}}}{\frac{kT_{\text{kin}}}{h\nu}\ln(1 + \frac{A_{J+1,J}\beta_\nu}{C_{J+1,J}})}.$$  \hspace{1cm} (1.9)
In the case of $A_{J+1,J}\beta_{\nu} < n(H_2)$, $T_{ex}$ becomes equal to $T_{\text{kin}}$, and then the local thermodynamic equilibrium (LTE) comes into effect. In the LTE case, the observed information contains only $T_{\text{kin}}$ and $\tau$ corresponding to the column density, while the density is calculated from the column density and the size of the region.

The gas density is directly determined through the observations of the tracer which is sub-thermally excited. In the non-LTE analyses, to solve the parameters ($T_{\text{kin}}$, $n(H_2)$, $\beta$, $\tau$), several lines that have different critical densities are usually observed and the combination of line ratios are used. In addition, the assumption of the cloud structure is necessary due to the $\beta$ dependency on the molecular cloud structure. The large velocity gradient (LVG) model (Goldreich & Kwan 1974; Scoville & Solomon 1974) is the most frequently used for the reasonable assumption of the cloud structure.

Previous Observations

In the molecular line analyses, the results represent the physical properties of the region where lines were emitted. The emitted region differs from line to line due to the variation of the critical density and opacity. Therefore, the selection of lines determines the density and temperature ranges that can be traced in the hierarchical structure of molecular clouds. Furthermore, several lines that have different critical densities are necessary for the derivation of the cloud properties as discussed previous subsection. For these reasons, the combinations of different critical density with similar emitting region, for example different transitions of molecules, had been used for the analyses.

Observations of physical properties of the molecular clouds were started immediately after the discovery of the $^{12}\text{CO}(J=2–1)$ line emission in the molecular cloud (Phillips et al. 1973). The early results observed toward the clouds provided ideas about the nature of the line-width (Goldsmith et al. 1975; Phillips & Huggins 1977; Phillips et al. 1979) and the hierarchical structure of the density (Kahane et al. 1985). Outflows were also observed and the physical properties were discussed (e.g., Plambeck et al. 1983; Levreault 1988). After the 1990’s, the developments in receiver technology enabled us the mapping study of the LVG analyses for the region with a few square degrees (Castets et al. 1990; Dutrey et al. 1993; Sakamoto et al. 1994; Plume et al. 2000; Martin et al. 2004; Nagai et al. 2007). However, these observations were carried out with coarse angular resolutions or only in small regions, mainly due to the fact that the multiline observations of the different transition costs a lot to conduct; usually they require multiple receivers or different telescopes.

The emission of the $^{13}\text{CO}(J=2–1)$ traces the region where the gas density is $10^2$–
10^4 cm^{-3} corresponding to the intermediate density region i.e., the envelope around the dense core (e.g., Kahane et al. 1985, Castets et al. 1990, Beuther et al. 2000, Zhu et al. 2003). Goldsmith et al. (1983), therefore, suggests the combination of a couple of transitions of a molecule is a good tracer of the cloud properties i.e., J=1–0 and J=2–1 of ^13CO. This method seems to trace the density fluctuation well (Castets et al. 1990; Dutrey et al. 1993), while we note here that their analyses include some error caused by the assumption that the \( T_{\text{kin}} \) is uniform for the dense region.

Recently, the combination of optically thin and thick lines with different transitions are found to be good tracers of the physical properties of the gas and the derived physical properties well reflect the star formation activities and the surrounding environments (e.g., Martin et al. 2004; Nagai et al. 2007; Mizuno et al. 2010; Minamidani et al. 2011; Torii et al. 2011; Nagy et al. 2012; Peng et al. 2012; Fukui et al. 2014). Hence we use the \(^{12}\text{CO}(J=2–1), \(^{13}\text{CO}(J=2–1), \) and \(^{13}\text{CO}(J=1–0) \) lines with the single component LVG analyses.

### 1.2 This Work

The aim of this thesis is to derive the physical properties of molecular clouds in multiple molecular transitions and to explore the relations between the properties and star formation. The large scale observations of the cloud properties would provide a new perspective for the characteristics of the molecular clouds, and also lead to elucidation of the evolution process of the molecular clouds; from clouds to dense cores. We also note that this fundamental knowledge of the properties of the molecular clouds is of increasing significance especially in the ALMA era; enabling us to compare the physical properties of the GMCs in the other galaxies with those of the Galaxy directly.

However, these observations have been delayed due to absence of the feasible telescope system (Figure 1.3). Recent progress of the receiver technology of the millimeter/sub-millimeter wave has been increasing the possibility of such observations. We therefore developed the telescope which is customized to conduct our goal. In the Chapter 2, we describe the design concept and implementation of the telescope which is optimized to survey the multilines of CO quickly. Chapter 3 presents the first survey results of the telescope. We have carried out full-sampling observations of both the Orion A and Orion B clouds, and compared them with the data in \( J=1–0 \) lines taken by the 4-m telescopes of Nagoya University to reveal the physical conditions in the GMCs. Finally, we summarize this thesis and give some future perspectives in
Chapter 4.
Figure 1.3: Plot of angular resolution vs. survey capability for the telescopes equipped with 100 or 200 GHz band receiver. Red and green colors indicate observable frequency bands of 100 and 200 GHz, respectively. Pentagon shape indicates the multi-beam receiver system, and other shapes indicate single-beam receiver system. Each plots are with the telescope name. Parenthesis notations indicate that the telescope operation was stopped.
Chapter 2

The 1.85-m Millimeter/Sub-millimeter Telescope

The primary aim of this thesis is to explore the physical properties of the molecular clouds. In the previous chapter, I discussed the utility of the multi line analysis of the CO rotational emission lines to determine the physical properties of the molecular clouds. In this chapter, I will discuss about the 1.85-m telescope which is newly prepared to achieve large scale CO multi line survey. The telescope has been developed by the radio astronomy group of the Osaka Prefecture University, and started science operation in January 2011. In Section 2.1, a brief introduction to the telescope is described. In Section 2.2 and 2.3, I present the telescope instruments and observing system, respectively. In Section 2.4.3, I discuss the performance of the developed telescope. Finally I summarize the chapter in Section 2.6.

2.1 Introduction

Molecular clouds are sites of star formation. Rotational transition lines of carbon monoxide (CO) have been widely used to investigate the distribution, physical properties, and kinematics of the molecular clouds to understand the star formation process in the Galaxy and external galaxies. The $J=1-0$ lines of $^{12}$CO, $^{13}$CO and C$^{18}$O are especially found to be good tracers of molecular mass due to the large abundance and to the low critical density for the excitation, enabling us to investigate the molecular distribution of low-density gas of $\sim$100 to high-density gas of $\gtrsim 10^4$ cm$^{-3}$. The
distribution of molecular gas in the Galaxy has been explored with relatively small-aperture telescopes, whose beam size is 1′–10′, because the molecular gas is widely distributed all along the Galactic plane, sometimes even over the high Galactic latitude areas. Such examples are the 1.2-m telescopes with a beam size of 8.7 at the Harvard-Smithsonian Center for Astrophysics (CfA) and Cerro Tololo Inter-American Observatory in Chile in the line of $^{12}$CO($J=1–0$) (e.g., Dame & Thaddeus 1985; Dame et al. 1987, 2001), as well as the 4-m telescopes in Nagoya and the NANTEN telescope in Chile, having a smaller beam size of 2.7 in the lines of $^{12}$CO($J=1–0$), $^{13}$CO($J=1–0$), and C$^{18}$O($J=1–0$) (e.g., Fukui & Yonekura 1998; Onishi et al. 2004). The Very Small Telescopes with a diameter of 60-cm in Nobeyama (Very Small Telescope 1: VST1) and in Chile (Very Small Telescope 2: VST2) of the Institute of Astronomy, the University of Tokyo, having the same beam size as the CfA 1.2-m telescopes, but tuned to the $^{12}$CO($J=2–1$) emission line, were also employed for a survey of the galactic plane, nearby molecular clouds, and the Large Magellanic Cloud (e.g., Sakamoto et al. 1994, 1995; Sorai et al. 2001). Recently, the new sideband-separating SIS receiver for the 230 GHz band was installed on the VST1 (AMANOGAWA telescope), which improved the observation efficiency. Thus, much larger surveys could be performed in the lines of $^{12}$CO($J=2–1$) and $^{13}$CO($J=2–1$) (Yoda et al. 2010). Yoda et al. (2010) suggest that the $J=2$ level is sub-thermally excited toward many of the molecular clouds, indicating that the $J= 2–1$ line can be used to trace the density of the molecular gas.

We also note here that under the assumption of the Local Thermodynamic Equilibrium (LTE), the integrated line intensity of the optically thin CO lines of $J=2–1$ is much less sensitive to the assumed excitation temperature in a range from 10 K to 30 K than the $J=1–0$ and $J=3–2$ lines (see appendix of Ginsburg et al. 2011). This fact indicates that the optically thin CO lines of $J=2–1$, $^{13}$CO and C$^{18}$O are better tools for deriving the column densities than those of the other transitions for relatively dense clouds where the $J=2–1$ transitions are close to the LTE.

Although the $J=1–0$ lines of CO are powerful tools to investigate the mass of the molecular content of the interstellar medium, the other transitions with different critical densities for the excitation are needed to investigate the local density and the temperature, which are important to know the evolutionary status of molecular clouds. Because $^{12}$CO lines tend to be optically thick toward relatively high-density regions, optically thin lines should be obtained to investigate the star-forming molecular gas. We therefore developed a telescope to observe molecular clouds in the $J=2–1$ lines of $^{12}$CO, $^{13}$CO, and C$^{18}$O simultaneously with an aperture size of 1.85-m in
order to derive better physical properties of molecular clouds of nearby star-forming regions. Simultaneous observations minimize the calibration error when comparing the line ratios and improving the observation efficiency; the angular resolution of $\sim 2.7$ is ideal to diagnose the dense cores extensively in the nearby star-forming regions (e.g., Onishi et al. 1996 in the case of Taurus). The simultaneous observations were achieved by developing a waveguide-type sideband-separating (2SB) receiver (Nakajima et al. 2007), and by installing a 16384-channel Fourier digital spectrometer with a frequency bandwidth of 1 GHz. An on-the-fly (OTF) scan is implemented to improve the observation efficiency and the mapping quality.

2.2 Telescope Instruments

The 1.85m telescope (Figure 2.1) was installed at the Nobeyama Radio Observatory by a radio astronomy group of Osaka Prefecture University. It is enclosed in a radome so as to prevent any harmful effects of the sunlight, strong wind, and precipitation in order to minimize the error in the telescope pointing and to stabilize the receiver system. It has a Cassegrain reflector antenna with Nasmyth beam-waveguide feed, and is mounted on an azimuth-elevation rotating structure (Figure 2.2).

2.2.1 Antenna and Optics

A 1.85-m main reflector with a focal length of 740 mm was installed. The designed surface accuracy was to 40 $\mu$m rms to achieve 345 GHz observations. Figure 2.3 shows the structure of the main reflector. The surface error due to the gravitational deformation and by the wind of 10 m s$^{-1}$ are estimated to be 13 $\mu$m rms or less by a finite-element analysis. The main reflector was made by mono block casting of AC4C aluminum alloy, followed by sandblasting and stress relieving annealing treatments. The surface was shaped by a turning center, and the resulting surface accuracy was measured to be 19 $\mu$m rms (Figure 2.4).

The optics is designed as the frequency-independent between the sub-reflector and the 2nd ellipsoidal mirror (M3) on a Gaussian beam propagation (Figure 2.5, Table 2.1) for molecular cloud observations in three bands at 115, 230, and 345 GHz.

2.2.2 Receiver System and Spectrometer

In order to achieve simultaneous observations of the $^{12}$CO, $^{13}$CO, and C$^{18}$O lines in a 230 GHz band, we developed a waveguide-type 2SB Superconductor-Insulator-
Figure 2.1: Photos of 1.85-m telescope at the Nobeyama Radio Observatory. The lower-left figure is with the radome installed.
Figure 2.2: Mechanical structure of the telescope. The beam path is indicated by the red line.
Figure 2.3: Drawings of the backup structure of the main reflector.

Figure 2.4: Measured surface error of the main reflector. We used a 3-D coordinate measuring machine, Shin Nippon Koki MM-3500, with a motorized probe head, Renishaw PH10M, with the main dish facing upward for the measurement. The measurement was carried out in a square grid pattern with an interval of 10 cm. The measurement error is 7 \mu m for the vertical direction.
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Figure 2.5: Optics parameters for a Gaussian beam.

Table 2.1: Optical parameters.

<table>
<thead>
<tr>
<th>Physical parameters [mm]</th>
<th>RF parameters [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Main dish</td>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>1850.00</td>
<td>230.00</td>
</tr>
<tr>
<td>Focus length of Main dish</td>
<td>Beam waist between Sub-ref and M1</td>
</tr>
<tr>
<td>740.00</td>
<td>5.60</td>
</tr>
<tr>
<td>Diameter of Sub-ref</td>
<td>Beam size at M2</td>
</tr>
<tr>
<td>185.00</td>
<td>22.87</td>
</tr>
<tr>
<td>Foci distance of Sub-ref (2C)</td>
<td>Curvature at M2</td>
</tr>
<tr>
<td>1180.00</td>
<td>318.28</td>
</tr>
<tr>
<td>Beam size at Sub-ref</td>
<td>Curvature at M2(image)</td>
</tr>
<tr>
<td>81.78</td>
<td>2111.60</td>
</tr>
<tr>
<td>Curvature at Sub-ref</td>
<td>Beam waist between M2 and M3</td>
</tr>
<tr>
<td>1105.97</td>
<td>19.64</td>
</tr>
<tr>
<td>Edge taper of Sub-ref</td>
<td>Beam size at M3</td>
</tr>
<tr>
<td>11.11</td>
<td>23.72</td>
</tr>
<tr>
<td>Distance</td>
<td>Curvature at M3</td>
</tr>
<tr>
<td>Sub-ref to M1 (plane)</td>
<td>1197.83</td>
</tr>
<tr>
<td>1197.83</td>
<td>2001.48</td>
</tr>
<tr>
<td>M1 to M2 (ellipsoidal)</td>
<td>Curvature at M3(image)</td>
</tr>
<tr>
<td>202.17</td>
<td>179.10</td>
</tr>
<tr>
<td>M2 to PLM_M1 (plane)</td>
<td>Beam waist between M3 and horn</td>
</tr>
<tr>
<td>724.90</td>
<td>3.11</td>
</tr>
<tr>
<td>PLM_M1 to PLM_M2 (plane)</td>
<td>Beam size at horn aperture</td>
</tr>
<tr>
<td>230.00</td>
<td>4.10</td>
</tr>
<tr>
<td>PLM_M2 to PLM_M3 (plane)</td>
<td>Curvature at horn aperture</td>
</tr>
<tr>
<td>100.00</td>
<td>47.00</td>
</tr>
<tr>
<td>PLM_M3 to M3 (ellipsoidal)</td>
<td>Dimensions in mm.</td>
</tr>
<tr>
<td>130.00</td>
<td>M2</td>
</tr>
<tr>
<td>156.00</td>
<td>276.59</td>
</tr>
<tr>
<td>M3 to Corrugated horn</td>
<td>M3</td>
</tr>
<tr>
<td>156.00</td>
<td>164.39</td>
</tr>
<tr>
<td>Focus length of ellipsoidal mirrors</td>
<td>Diameter of horn aperture</td>
</tr>
<tr>
<td>M2</td>
<td>12.74</td>
</tr>
<tr>
<td>M3</td>
<td>47.00</td>
</tr>
<tr>
<td>Dimensions in mm.</td>
<td></td>
</tr>
</tbody>
</table>
Superconductor (SIS) mixer receiver. The rest frequencies of $^{12}\text{CO}(J=2–1)$, $^{13}\text{CO}(J=2–1)$, and $^{18}\text{O}(J=2–1)$ are 230.5380000 GHz, 230.3986765 GHz, and 219.5603568 GHz, respectively, and thus when we use the local frequency of ~225 GHz, the IF frequencies fall into a 4–8 GHz IF band. The receiver noise temperature in Single Side Band (SSB) mode was in the range of 70 to 100 K by the Y-factor method. The image-rejection ratios were in the range of 10 to 20 dB.

The intermediate frequency (IF) circuit is designed to handle the three CO lines simultaneously (Figure 2.6). The role of the IF circuit is to adjust the frequency range and the power, for the spectrometer. In order to correct Doppler shift arise from relative motion between the observer and local standard of rest (LSR), the 2nd local (LO) frequency is used for Doppler tracking. In this frequency configuration, LSB includes $^{13}\text{CO}$ and $^{18}\text{O}$ lines at the 1st IF frequency band (4–8 GHz). Because the Doppler shift frequency differs with the rest frequency of the target line, we correct $^{13}\text{CO}$ and $^{18}\text{O}$ separately. Finally, separated three bands are merged, and introduced to the spectrometer.

A Fast Fourier Transform (FFT) spectrometer, Acquiris AC240 (Benz et al. 2005), is installed at the end of the LO chain. The maximum sampling rate of the AD is 2 Gsps, and the total bandwidth is 1 GHz, divided into 16384 channels with a channel separation of 61.035 kHz. The input level ranges from 50 mV to 5 V, and the 5 V range is used to minimize the effect of spurious noise from the circuit inside. We measured the linearity at the 5 V input range, and found that the spectrometer exhibits linearity within the input-signal level from −15 dBm to 15 dBm. The Allan time is measured to be ~ 1000 s, which is consistent with Benz et al. (2005).

### 2.2.3 Control System

The telescope drive and control system is a key to realize efficient observations. The maximum slew speed and acceleration should thus be carefully selected. The telescope and various equipment are controlled and monitored on a Linux PC system with a server-client architecture via TCP/IP socket connections. The whole system consists of the following 4 components (Figure 2.7): 1, Server programs for controlling the telescope/equipment mostly written in C language; 2, Client Python modules for communicating with the server modules; 3, MySQL database for storing the environmental data and the telescope/equipment status; 4, Visualization of the database in a web-base application developed with Python.

Hardware controls and monitors that require precise timing and/or speed have been developed in the C language, and are implemented as a server with a common
Figure 2.6: Block diagram between the receiver horn and the spectrometer.
Figure 2.7: Schematic diagram of the telescope control system.
calling interface with the clients; the other servers are written in Python. In order to make the observation program easy and flexible, each program that connects to the server is encapsulated and modularized by Python scripts, and then all of the observation procedures can be described in Python. Each server program consists of three parts: 1, hardware control via such as digital I/O, A/D, GPIB, and RS-232C; 2, network sockets that connect to the client; 3, updating MySQL database for the status. Because the second and the third parts are common for all of the servers, they are modularized to be used from all of the servers for ease of maintenance. Each server has a corresponding client Python module that can be included in the Python script with an "import" command. The servers and the client modules contact each other via TCP/IP sockets, and then a client module, i.e., the observation program can be executed on any PCs if it can be accessible via network. We normally use three PCs for observations. One is for the servers, including motor control, hot load control, and so on; another is a board computer installed in the spectrometer AC240 for data acquisition; the other is for executing observation scripts and for data storage.

2.3 Observing Software

In this subsection, we describe the software system which is developed for the 1.85-m telescope. In the 1.85-m telescope, all the operations including the observations, status logging, evaluations of the devices, data managements, and visualization of the data are conducted with a unified system based on python. Automatic operations are realized owing to such the unified system, and then it brings us a very high observation efficiency with no machine dead-time and the minimized burden for the operator who conducts around-the-clock monitoring during the observation season. In addition, we designed the system as flexible with change by using the object oriented programming and the polymorphism technique. The system is therefore highly modularized with small classes. This system is installed to the 1.85-m, and ported to the SPART telescope which is one of the Nobeyama Millimeter Array (NMA), and also is under the consideration to apply the NANTEN2 telescope.

2.3.1 Measurement Device Controlling Package: pymeasure

In the system, pymeasure modules are located in the lowest level layer. The pymeasure undertake a role of the controlling of the devices including microwave measurement instruments (e.g., signal generators, spectrum analyzers, power meters), sensors (e.g.,
2.3. OBSERVING SOFTWARE

temperature monitors, pressure monitors), motors, A/D, and I/O. The communication standards are compatible with GPIB, Serial, USB, and Socket (TCP/IP). Since this package offers a versatile method, we released it for the community through the following URL, https://github.com/ars096/python-microwave-measurement-tools.

2.3.2 Telescope Observation System

The daily operation is composed of a cycle of the real observations and the preparation observations including measurements of the state of the atmosphere, telescope pointing calibrations, and receiver intensity calibrations. The flow of the cycle is shown in the Figure 2.9. This flow is executed automatically by the manager module in the obs package (Figure 2.8). There are 6 layers in the obs package, manager layer, observer layer, operator layer, controller layer, telescope parts layer, and device layer.

Manager Layer

The manager layer is composed of the manager class implemented in the manager module which controls the telescope operation. In the cycle (Figure 2.9), the module firstly conducts the preparation observations and evaluates the results whether they deserve to start the real observations or not. When the condition is good, the manager gets the observation target from the queue table in the database and calls the observer class function to start the real observation.

Observer Layer

The observer layer is composed of the observer classes corresponding to mode of the observations. The classes are wrapper classes of the operator classes. This module provides the log of the operation, and supports future expansion of the functions.

Operator Layer

The operator layer is composed of the operator classes corresponding to mode of the observations (e.g., position-switching mode, OTF mode, skydip observation). The procedures of the observations are implemented in the each operator classes by calling the functions provided from the controller class. The flow chart of the procedure of the position-switching observing mode is shown in Figure 2.10 for example.
Figure 2.8: Class diagram of the observation package.
Figure 2.9: Flow chart of the automatic observation scheme.
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Figure 2.10: Flow chart of the position-switching observation.
Controller Layer

The controller layer is composed of the controller class implemented in the controller module. The class provides the interface of the basic function of the telescope operation (e.g., move the telescope, acquire the spectrum data, initialize the system to start the observation). All the functions that the operator class uses are implemented in the controller class, and the operator class is forbade to access device classes directly.

Telescope Parts Layer

This layer is composed of the main parts of the telescope instruments including antenna drives, beam transmission controller, receiver, and backend system. The layer provides the interface to operate the main parts of the telescope instruments.

Device Layer

The device layer is mainly composed of the pymeasure module. This layer provides the control of the devices.

2.3.3 Realtime Qlook System

In the large-scale survey project, management of the large quantities of observed data is becomes a serious problem. For instance in the 1.85-m telescope projects, the telescope is able to conduct the OTF observation in 10 times per day, and then the obtained number of the spectra amounts to \(~4 \times 10^4\) corresponding to about 5 GB for each days. In order to confirm the quality of the data automatically, we developed the web-based quick look system (Figure 2.11). The application is constructed on the CherryPy web framework of python, and operated with the Apache HTTP server.

2.4 Performance

2.4.1 Pointing Accuracy

Given a beam size of \(~2.7\), the pointing accuracy should be much less than that, and the goal would be less than 30". The pointing model is empirically derived by iterating the pointing measurements based on the models for other telescopes (e.g., Ulich 1981; Nakajima et al. 2007). The telescope pointing calibration was carried out in a twofold manner: the first was to use an optical telescope attached on the
Figure 2.11: Schematic diagram of the web-based Q-look system.
telescope to measure the axis misalignments and flexures; the second was to observe the Sun, Moon, and point-like objects with the radio telescope to correct for the off-axis placement of the receiver, encoder offsets, and gravitational flexure. The refraction was corrected by using a Positional Astronomy Library SLALIB (Wallace 1994). The pointing parameters were stored in a text file, and read by the observation program. The DUT1 at the observation time is from the International Earth Rotation and Reference Frame Service (IERS) BULLETIN-A.

2.4. PERFORMANCE

Optical Pointing Calibration

There are only a limited number of point-like sources for a small-aperture telescope at mm-submm wavelengths suitable for the pointing calibration. The pointing calibration by using an optical telescope attached on the radio telescope has therefore been widely performed. In the present case, the axis misalignments, encoder offsets, and flexures for the azimuth and elevation terms are considered for the calibration. The following equations are used:

\[ \cos(El) dAz = A_1 \sin(El) + A_2 + A_3 \cos(El) + B_1 \sin(Az) \sin(El) + B_2 \cos(Az) \sin(El) \]

and

\[ dEl = B_1 \cos(Az) + B_2 \sin(Az) + B_3 + G_1 El, \]

where \( Az \) and \( El \) are the encoder values for the azimuth and elevation angles, respectively; \( dAz \) and \( dEl \) are the corrections, \( A_1 \) is the non-prependicularity between the mount azimuth and elevation axes, \( A_2 \) is the collimation error, \( A_3 \) is the encoder zero offset, \( B_1 \) is the azimuth axis misalignment of north-south direction, \( B_2 \) is the azimuth axis misalignment of east-west direction, \( B_3 \) is the elevation encoder zero offset, and \( G_1 \) is for the gravitational flexure correction. These terms are derived from a collection of 100 or more pointing measurements all over the sky. The CCD output of the optical telescope is read by a video board on a PC, and then a program for the calibration calculates the position of a star and the positional error. One set of the measurement takes about one hour. Figure 2.12 shows a result of the optical pointing calibration, showing that the pointing rms error is measured to be about 4", which is less than one-tenth of the HPBW.
Radio Pointing Calibration

We performed one-directional horizontal and vertical total power scans toward the Sun and the full Moon (Figure 2.13). We derived the encoder offsets and gravitational flexure from the measurement. After the adjustment, spectral OTF mappings were carried out toward a point-like or peaked molecular distribution: mainly toward IRC+10216 and Orion KL. The off-axis placement of the receiver only depends on the elevation angle with a sine function. It is therefore hard to derive the term because the El angles only range from 20° to 80°. We then carefully aligned the optics and the position of the cryostat by developing specialized jigs. As a result, we found that the effect of this term is not seen in the pointing measurement, and the peak-to-peak error of the radio pointing measurement is observed to be about 30°.

2.4.2 Beam Characteristics

Beam Size

The beam pattern has been obtained as the differential of the scanning data of the Sun. The half power beam width (HPBW) of the telescope is measured to be 2.7 at 230 GHz, assuming a Gaussian-shape beam pattern. Figure 2.14 illustrates the result.
of an OTF mapping toward IRC+10216 and it shows that the beam pattern is nearly circular symmetry.

**Intensity Calibration**

The beam efficiency is normally derived by observing objects with known temperature with a source extent roughly equal to, or smaller than, the size of the main beam. Although the planets are the best targets for the measurement, they are too small to be observed accurately with the 1.85-m telescope because of large beam dilution. We thus use the "standard source" to adjust the temperature scale from $T_A^*$ to $T_R^*$ (see Kutner & Ulich 1981 for the definitions). The primary source for the calibration is Orion KL, which is the strongest source in $^{12}$CO($J=2$–$1$). We made an OTF observation toward the Orion KL region ($\alpha_{J2000} = 05^h35^m14^s46, \delta_{J2000} = -05^\circ22'29''6$) with the 1.85-m telescope for the measurement. The maximum antenna temperature is observed to be 52.5 K in $T_A^*$ at this time. We then obtained an OTF mapping observation toward Orion KL with the NANTEN2 telescope to be used for convolutions to the beam sizes of the KOSMA and 1.85-m telescopes, and then compared the results with a $T_R^*$ of 70 K with the KOSMA (Schneider et al. 1998). The $T_R^*$ of NANTEN2 and the 1.85-m telescope are then estimated to be 78 K and 63.5 K, respectively. As an independent confirmation, we convolved OTF mapping data taken with the 1.85-m telescope to the same angular resolution with the 60 cm telescope, and obtained a convolved $T_A^*$ of 29.5 K. The $T_A^*$ with the 60-cm is 32 K (Nakajima et al. 2007) with...
an image rejection ratio of 13.9 dB. The beam efficiencies in Nakajima et al. (2007) and in Sakamoto et al. (1995) are 97.4% and 93%, respectively, and the estimated $T^*_R$ values of Orion KL for the 1.85-m telescope are calculated to be 53 K and 63K, respectively. These values are consistent with that derived from a comparison with KOSMA data within a factor of 10%. Recently, Yoda et al. (2010) derived the beam efficiency of the 60-cm telescope to be 73% by observing the Sun with a wire grid installed in front of the receiver so as to avoid saturation of the SIS mixer. If we adopt this value, the $T^*_R$ for the 1.85-m telescope is estimated to be 77 K, which is larger than the first estimation by a factor of 20%. The beam efficiency of the 60-cm telescope of 73% is apparently too small for the simple optics of the telescope, and the additional installation of the wire grid in the optics system may need a careful calibration. Here, we thus adopt $T^*_R$ of Orion KL for the 1.85-m telescope to be 63 K with possible uncertainty of $\sim 10\%$. 

Figure 2.14: Integrated intensity map of the $^{12}\text{CO}(J=2-1)$ toward the carbon star IRC+10216. The maximum intensity is normalized to the contour scale of 100. Because the $^{12}\text{CO}$ distribution is much smaller than the beam size of 2.7 (e.g., Truong-Bach et al. 1991), the intensity distribution resembles the beam pattern.
2.4.3 System Noise Temperature and Image Rejection Ratio

The waveguide-type sideband-separating SIS receiver system consists of two SIS mixers, and the receiver noise temperatures of the both mixers are about 50 K in DSB. The SSB noise temperature of the sideband-separating SIS receiver was measured to be about 75–100 K \( (T_{rx}) \) for both the Lower Side Band (LSB) and Upper Side Band (USB). The typical SSB noise temperatures of the system including the atmosphere toward the zenith is in the range of 200 to 400 K, derived from the chopper wheel calibration. The system noise temperature can also be estimated from the following equation:

\[
T_{sys} = \frac{F_{eff}T_{sky}(1 - e^{-\tau}) + (1 - F_{eff})T_{amb} + T_{rx}}{F_{eff}e^{-\tau}},
\]

where \( F_{eff} \) is the forward efficiency, basically the fraction of power in the forward beam of the feed, which can be derived from the sky tipping; \( T_{sky} \) is the sky temperature, \( T_{amb} \) is the ambient temperature and \( \tau \) is the optical depth of the atmosphere. \( F_{eff} \) is measured to be 0.82; assuming \( T_{sky} = T_{amb} = 273 \) K with a best sky condition of \( \tau = 0.12 \), the system noise temperature is calculated to be 205 K. This is consistent with that from the \( T_{sys} \) measurement mentioned below, which indicates that there is no other significant loss in the optics. The image rejection ratios are measured using the same method as that of Nakajima et al. (2007); they are 13dB at both the USB and LSB ports, respectively.

2.4.4 Atmospheric Condition at NRO in the 230 GHz Band

We performed sky tipping and an observation of a standard source for the temperature calibration every few hours. The optical depths of the atmosphere toward the zenith and the system noise temperatures were recorded. Figure 2.15 shows the distribution of the optical depths during the winter season is typically 0.15–0.3, which corresponds to a system noise temperature including the atmosphere toward the zenith of 200-300K.

2.5 CO Observations

The first simultaneous observation of the \( J=2–1 \) transitions of \(^{12}\text{CO}, ^{13}\text{CO}, \) and \(^{18}\text{O} \) has been achieved in 2009 September. Fig.2.16 shows a chopper-wheel calibrated spectrum with a frequency range from 0 to 1 GHz. We have made OTF maps toward Orion KL and S140 for the commissioning. Fig.2.17 shows the maps toward S140 in
three lines. The first science observations have started from 2011 January and have continued until 2011 May. All the mapping observations have been carried out with the OTF mapping. The typical observation unit of the OTF scan is a 1°×1° tile with a dumping time of 1 sec with a spatial interval of 1′. The spatial separation across the scan is 1′, and then the 60×60 spectra are obtained during the unit observation. The observation needed for the unit observation is typically 100 minutes, somewhat depending on the separation of the OFF point, and the observation efficiency, a ratio total ON time over the total observation time, is calculated to be about 60%. During the 2011 season, we have observed Orion A/B cloud (Nishimura et al. 2014, submitted to ApJS), Cygnus OB7 (Dobashi et al. 2014 in preparation), Monkey Head Nebulae (Shimoikura et al. 2013), Galactic Plane, and Taurus molecular cloud.

Figure 2.15: Distribution of the optical depths (upper) and the system noise temperature including the atmosphere toward the zenith (lower) between 2012 January and April. The optical depth of ~ 0.4, corresponding to a system noise temperature of ~ 400 K, indicated by the solid lines in the figures, is used for the threshold value for the observations. About 60% of the period shows a better sky condition than this threshold.
2.6 Summary

We have newly developed a mm-submm telescope with a main reflector diameter of 1.85-m installed at the Nobeyama Radio Observatory. The main dish and the optics are created so as to achieve molecular line observations at 115, 230, and 345 GHz. The current target frequency is 230 GHz band, and the 2.7 beam size (FWHM) of the telescope is suitable to obtain a large scale distribution of molecular gas which also can be compared with large-scale observation data in various wavelengths. The development of a waveguide-type 2SB SIS receiver enables us to observe molecular clouds in the molecular rotational lines of $J=2–1$ of carbon monoxide and the isotopes ($^{12}$CO, $^{13}$CO, $^{18}$O) simultaneously. In the IF chain, the three spectrum bands are down-converted and merged into the frequency band from 0 to 1 GHz. We then installed a Fast Fourier Transform (FFT) spectrometer Acqiris AC240 at the end of the IF chain, whose total bandwidth is 1GHz, divided into 16384 channels. The telescope and various equipments are controlled and monitored on a Linux PC system with a server-client architecture via TCP/IP socket connection. In order to make the observation program easy and flexible, each program that connects to the server is encapsulated and modularized by Python scripts, and then all the observation procedures can be described in Python.

The commissioning of the telescope confirmed the performance of the new telescope. The beam size (HPBW) was measured to be 2.7', and the typical system noise temperatures including the atmosphere are from 200 to 400 K. The pointing accuracy is observed to be better than 30" (peak-to-peak). Implementation of the OTF
mapping was successful, and the typical observation efficiency, a ratio total ON time over the total observation time, is calculated to be about 60%. With this telescope, we have observed Orion A/B cloud, Cygnus OB7, Monkey Head Nebulae, Galactic Plane, and Taurus molecular cloud, whose results will be published subsequently. We have also been developing a dual-polarization receiver, with which we can observe both polarizations simultaneously. The commissioning observation was successful in 2012 May, and the observation efficiency will be expected to be improved by a factor of 2 from the next observation season.
Chapter 3

Observation of the Orion Giant Molecular Clouds: Revealing the Physical Properties of the Clouds

ABSTRACT

We present fully sampled ~ 3’ resolution images of the $^{12}$CO($J = 2–1$), $^{13}$CO($J = 2–1$), and C$^{18}$O($J = 2–1$) emission taken with the newly developed 1.85-m mm-submm telescope toward the entire area of the Orion A and B giant molecular clouds. The data were compared with the $J = 1–0$ of the $^{12}$CO, $^{13}$CO, and C$^{18}$O data taken with the Nagoya 4-m telescope and the NANTEN telescope at the same angular resolution to derive the spatial distributions of the physical properties of the molecular gas. We explore the large velocity gradient formalism to determine the gas density and temperature by using the line combinations of $^{12}$CO($J = 2–1$), $^{13}$CO($J = 2–1$), and $^{13}$CO($J = 1–0$) assuming uniform velocity gradient and abundance ratio of CO. The derived gas temperature is mostly in the range of 20 to 50 K along the cloud ridge with a temperature gradient depending on the distance from the star forming region. We found the high-temperature region at the cloud edge facing to the H$_{II}$ region, indicating that the molecular gas is interacting with the stellar wind and radiation from the massive stars. The derived gas density is in the range of 500 to 5000 cm$^{-3}$. The high density regions ($\gtrsim$ 2000 cm$^{-3}$) are located toward the cloud edge facing to the H$_{II}$ region, suggesting the compression of the molecular gas by the stellar wind and radiation. In addition, we compared the derived gas properties with the Young Stellar Objects distribution obtained with the Spitzer telescope to investigate the
relationship between the gas properties and the star formation activity therein. We found that the gas density and star formation efficiency are well positively correlated, indicating that stars form effectively in the dense gas region.

### 3.1 Introduction

Most of stars are formed in Giant Molecular Clouds (GMCs) in the Galaxy (e.g., Lada 1998). Molecular rotational transitions have been used to investigate the physical properties of the molecular gas to be compared with the star formation activities therein. The lowest transition ($J = 1–0$) lines of CO and its isotopes are good mass (or column density) tracers of molecular gas from relatively low-density regions ($\sim 10^2$ cm$^{-3}$) to high-density regions ($\gtrsim 10^4$ cm$^{-3}$). This is because the molecule is the most abundant in the interstellar medium (ISM) except for molecular hydrogen and helium, and also because the Einstein coefficient for spontaneous emission, $A_{10}$, is small, for which CO can be excited by collision even at relatively low density, making the low rotational transitions of CO good probes of the molecular gas. The $J = 1–0$ lines of $^{12}$CO and $^{13}$CO have, therefore, been used to carry out large-scale observations covering the large areas of various nearby star forming sites (e.g., Dame et al. 2001; Dobashi et al. 1994; Tachihara et al. 1996; Mizuno et al. 1998; Kawamura et al. 1998; Onishi et al. 1999; Yonekura et al. 2005; Ridge et al. 2006; Jackson et al. 2006; Goldsmith et al. 2008). Such large-scale surveys have provided us invaluable information to characterize the morphological and physical properties of molecular clouds. Meanwhile, the higher excitation lines such as CO($J = 2–1$) have been used to determine the local densities and temperatures by making use of the fact that they have higher critical densities for the excitation, which are also quite important for us to diagnose the evolutionary status of the molecular clouds (e.g., Sakamoto et al. 1995; Beuther et al. 2000; Yoda et al. 2010; Polychroni et al. 2012). However, such observations were conducted only at coarse angular resolutions or only toward small regions, mainly because the development of sensitive receivers at the high frequencies had been very difficult and because the opacity of the earth atmosphere is high at low altitude sites.

The Orion star forming region contains nearest GMCs with massive star clusters, and then it is one of the most suitable site to investigate the process of star formation and the effect on the parent cloud. It includes two GMCs, Orion A and Orion B, whose distance is estimated to be 410 pc (e.g., Menten et al. 2007; Sandstrom et al. 2007; Hirota et al. 2007). Extensive observations of the whole Orion region have been
made in $^{12}\text{CO}(J = 1–0)$ (Kutner et al. 1977; Maddalena et al. 1986; Wilson et al. 2005), $^{12}\text{CO}$ and $^{13}\text{CO}(J = 1–0)$ (Ripple et al. 2013), $^{12}\text{CO}(J = 2–1)$ (Sakamoto et al. 1994), $^{12}\text{CO}(J = 3–2)$ and $C_1^+(3P_1–3P_0)$ (Ikeda et al. 2002). Those of the Orion A cloud have been made in $^{12}\text{CO}(J = 1–0)$ (Shimajiri et al. 2011; Nakamura et al. 2012), $^{13}\text{CO}(J = 1–0)$ (Bally et al. 1987; Nagahama et al. 1998), $^{13}\text{CO}$ and $C^{18}\text{O}(J = 3–2)$ (Buckle et al. 2012), CS($J = 1–0$) (Tatematsu et al. 1993), CS ($J = 2–1$) (Tatematsu et al. 1998), and $H^{13}\text{CO}^+(J = 1–0)$ (Ikeda et al. 2007). Those of the Orion B cloud have been made in $C^{18}\text{O}(J = 1–0)$ and $H^{13}\text{CO}^+ (J = 1–0)$ (Aoyama et al. 2001), $^{13}\text{CO}$ and $C^{18}\text{O}(J = 3–2)$ (Buckle et al. 2010), CS ($J = 2–1$) (Lada et al. 1991), and $H^{13}\text{CO}^+ (J = 1–0)$ (Ikeda et al. 2009). These observations revealed that the clouds are full of filaments and cores (Nagahama et al. 1998; Aoyama et al. 2001) and are affected by UV radiations from the nearby OB stars (Bally et al. 1987; Wilson et al. 2005). The northern part of the Orion A cloud and the entire Orion B cloud are exposed to the strong UV radiation field of $G_0 = 10^{4–5}$ (Tielens & Hollenbach 1985; Kramer et al. 1996). On the other hand, the central and southern parts of the Orion A are of low UV field and show quiescent low-mass star formation. The difference in the activity of the star formation should result in different physical properties of the molecular gas.

Sakamoto et al. (1994) carried out a large area $^{12}\text{CO}(J = 2–1)$ mapping of the Orion A and Orion B clouds, and compared them with the $^{12}\text{CO}(J = 1–0)$ data obtained by Maddalena et al. (1986) on the same observing grids at a same angular resolution of 9′. They observed a systematic variation of the $^{12}\text{CO}(J = 2–1)/^{12}\text{CO}(J = 1–0)$ intensity ratio over the entire extents of the GMCs, reflecting the physical properties of the molecular gas there. It was, however, difficult to derive the properties precisely, especially toward the ridge area where star formation is taking place because the optical depth toward the ridge is expected to be very large for the $^{12}\text{CO}$ emission. The angular resolution (9′) corresponds to a spatial resolution of $\sim 1$ pc at the distance of the Orion clouds. Because the Jeans length of the gas with $n(\text{H}_2) \sim$ a few $\times 100$ cm$^{-3}$ and $T \sim 10$ K is estimated to be $\sim 1$ pc, observations with a spatial resolution of $< 1$ pc are needed to investigate the physical properties of the individual clouds and the dynamical state.

We developed a 1.85-m mm-submm telescope for large-scale molecular observations in $J = 2–1$ lines of $^{12}\text{CO}$, $^{13}\text{CO}$, and $C^{18}\text{O}$ (Onishi et al. 2013). The purpose of the telescope is to reveal the physical properties of the molecular clouds extensively at an angular resolution of $\sim 3′$. As one of the major survey projects of the telescope, we have carried out a full-sampling observation of both the Orion A and
Orion B clouds, and compared them with the data in $J = 1–0$ lines taken by the 4-m telescopes of Nagoya University. This paper is organized as follows: in Section 2, the observations and data reduction procedures of the 1.85-m telescope and the 4-m telescopes are described. In Section 3, we present results of CO($J = 2–1$) and CO($J = 1–0$) observations. In Section 4, we describe our analyses and present the derived physical properties of the Orion molecular clouds. In Section 5, we discuss the cloud properties, star formation activity of this region, and the surrounding environment. Finally we summarize the paper in Section 7.

3.2 Observations

3.2.1 $^{12}$CO($J = 2–1$), $^{13}$CO($J = 2–1$), and C$^{18}$O($J = 2–1$)

Observations of the $J=2–1$ transitions of $^{12}$CO, $^{13}$CO, and C$^{18}$O were carried out with the 1.85-m telescope installed at Nobeyama Radio Observatory (NRO) which is enclosed in a radome that prevents the telescope structure distortion due to outdoor conditions (e.g., precipitation, wind, and sunlight). At 230 GHz, the telescope has a beam size of 2.7 (HPBW) which was measured by continuum scans of the Jupiter. We used a two sideband separating (2SB) superconductor-insulator-superconductor (SIS) mixer receiver to observe $J = 2–1$ lines of $^{12}$CO, $^{13}$CO, and C$^{18}$O simultaneously. The typical noise temperature of the receiver $T_{RX}$ was measured to be $\sim 100$ K (single sideband) and the image rejection ratio (IRR) was measured to be 10 dB or higher. A Fast Fourier Transform (FFT) spectrometer with 1 GHz bandwidth and 61 kHz frequency resolution is installed as the backend system. We used the spectrometer for the observations in the three lines by dividing the frequency band into three parts. Each part has a velocity coverage and a velocity resolution of $\sim 250$ km s$^{-1}$ and 0.08 km s$^{-1}$, respectively. Further information of the telescope is described by Onishi et al. (2013).

The intensity calibration was carried out by observing a standard source, Orion KL, as described in Onishi et al. (2013). They estimated the uncertainty of the calibration to be $\sim10\%$. The other factor that may affect the calibration accuracy is the beam coupling to the sources with different extents. Figure 4 of Onishi et al. (2013) shows that there is no large-scale deformations affecting the strength of the error beam, and the main dish was made by monobloc casting, which has no effect of small-scale fluctuations of the surface like misalignments of panels sometimes seen in large telescopes (e.g., Greve et al. 1998 for the case of IRAM 30m). Onishi et al. (2013)
also showed that the beam is nearly circular symmetry without significant minor lobes observed. The typical antenna temperature toward the Orion KL is \(~45\) K in \(^{12}\text{CO} (J=2–1)\) after the correction of the effect of the spillover to the image sideband. The brightness temperature of the Orion KL is \(63\) K in \(^{12}\text{CO} (J=2–1)\) (Onishi et al. 2013). Therefore, the typical scaling factor from the antenna temperature to \(T^*_R\) is \(1/0.7\). The moon efficiency was measured to be \(~70\)% with an error of \(~10\)%.

All of these facts indicate that the calibration error due to the beam coupling to the sources with different extents is smaller than that for the intensity calibration to the \(T^*_R\) scale, which is \(~10\)% (Onishi et al. 2013). Therefore, the uncertainty of in the calibration is estimated to be \(~10\)% here.

The observations were carried out from 2011 January to 2011 May. The \(^{12}\text{CO},^{13}\text{CO},\) and \(\text{C}^{18}\text{O}\) lines were observed simultaneously. The system noise temperatures including the atmospheric attenuation \(T_{\text{sys}}\) were in the range of 200 to 400 K for the three lines. We have covered 55 deg\(^2\) around the Orion A and Orion B molecular clouds. The area was divided into 55 submaps of \(1^\circ \times 1^\circ\). We observed each submap using the on-the-fly (OTF) mapping technique along the galactic coordinates. The scan data were obtained with a fully sampled grid of 1’. We selected 30 different OFF positions toward where we confirmed that the \(^{12}\text{CO}\) emission is absent at the rms noise level of \(~0.1\) K at a velocity resolution of 0.08 km s\(^{-1}\). In this paper, we use the calibrated \(T^*_R\) scale (Kutner & Ulich 1981). Before observing each submap, we observed the Orion KL (\(\alpha_{2000} = 05^h35^m14^s46, \delta_{2000} = -05^\circ22'29"6\)) for an intensity calibrations to \(T^*_R\) scale by assuming its peak temperature of \(^{12}\text{CO} (J = 2–1)\) is \(63\) K (Onish et al. 2013). We applied each scale factor obtained by the \(^{12}\text{CO}\) observations for the intensity calibrations of \(^{13}\text{CO}\) and \(\text{C}^{18}\text{O}\). We subtracted a polynomial curve from each spectrum to ensure the linear baseline, and resampled the raw OTF data onto the 1’ grid by convolving them with a Gaussian function. The rms noise of the resulting data, \(\Delta T^*_R\), is typically \(~0.45\) K at the velocity resolution of 0.3 km s\(^{-1}\) with an effective beam size of \(3'4\). In addition, we made a moment masked cube (e.g., Dame 2011) to suppress the noise effect in the velocity analysis. The moment masked cube has zero values at the emission free pixels, which is useful to avoid a large error arising from the random noise. The emission free pixels are determined by identifying significant emission from the smoothed data whose noise level is much lower than the original data.
3.2.2 $^{12}$CO($J = 1–0$), $^{13}$CO($J = 1–0$), and C$^{18}$O($J = 1–0$)

The $^{12}$CO($J = 1–0$) and $^{13}$CO($J = 1–0$) data were taken with the two 4-m millimeter-wave telescopes at Nagoya University (Kawabata et al. 1985; Fukui et al. 1991). The beam size of the telescopes were 2.7 (HPBW) at 110 GHz. Each telescope was equipped with a 4 K cooled superconducting mixer receiver (Ogawa et al. 1990), which provided typical single sideband system noise temperatures of $\sim$400 K and $\sim$150 K for $^{12}$CO and $^{13}$CO frequency bands, respectively, including the atmospheric attenuation. The spectrometers were acousto-optical spectrometers (AOSs) with the 40 MHz bandwidth and 40 kHz frequency resolution, corresponding to a velocity coverage and resolution of 100 and 0.1 km s$^{-1}$, respectively. The data were obtained by frequency switching mode with a grid spacing of 4$'$ and 2$'$. The rms noise level is better than 0.5 K in $T_\ast$R scale. The survey data were partially published by Nagahama et al. (1998) for $^{13}$CO($J = 1–0$) data of the Orion A.

The C$^{18}$O($J = 1–0$) data were taken with the NANTEN 4-m telescope (Mizuno & Fukui 2004) which is equipped with the same receiver and spectrometer as the Nagoya University 4-m telescopes described above. The C$^{18}$O($J = 1–0$) observations were carried out toward the region where the $^{13}$CO($J = 1–0$) line emission is strong. The data were obtained by frequency switching mode at a grid spacing of 2$'$. The rms noise level is better than 0.1 K in $T_\ast$R scale. The survey data were partially published by Aoyama et al. (2001) for the observation of the Orion B.

3.3 Results

3.3.1 Spatial distribution

$^{12}$CO($J = 2–1$) and $^{12}$CO($J = 1–0$)

Figure 3.1 shows velocity-integrated intensity maps of $^{12}$CO($J = 2–1$) and $^{12}$CO($J = 1–0$) observed with the 1.85-m telescope and the 4-m telescopes, respectively. The intensities are calculated by integrating the spectra between $v_{\text{LSR}} = 0$ and 20 km s$^{-1}$ where the emission exists. The Orion A and B molecular clouds are fully covered with significantly improved sensitivity, angular and frequency resolutions compared with previous $^{12}$CO($J = 2–1$) observations carried out by Sakamoto et al. (1994). As pointed out by Sakamoto et al. (1994), we found that the two transitions of $^{12}$CO exhibit a similar spatial distribution on a large scale. However, small-scale differences are seen in the lower intensity regions. Actually, in the higher intensity
Figure 3.1: Integrated intensity maps of (a) $^{12}$CO($J = 2–1$) with peak intensity of 431 K km s$^{-1}$ and (b) $^{12}$CO($J = 1–0$) with peak intensity of 359 K km s$^{-1}$ toward the Orion A and B molecular clouds. The velocity range used for the integration is $0 < V_{\text{LSR}} < 20$ km s$^{-1}$ for both of the maps. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
3.3. RESULTS

Figure 3.2: Explanatory map of the $^{12}$CO emission features. Gray scale is the peak intensity distributions of the $^{12}$CO($J = 2–1$) emission ranging from 0.5 to 25 K. Details of the features are described in subsection 3.3.1.

regions ($> 100$ K km s$^{-1}$) both images exhibit almost similar distributions, while in the lower intensity regions ($< 10$ K km s$^{-1}$) the $J = 1–0$ emission is apparently more widely distributed than $J = 2–1$ emission. In the following, we describe the spatial distribution for the Orion A and B in more detail (see Figure 3.2).

The Orion A molecular cloud is distributed almost parallel to the galactic plane at $b = -19\degree 5$. The maximum intensities of $^{12}$CO($J = 2–1$) and $^{12}$CO($J = 1–0$) are both found at the position of Orion KL ($l = 208\degree 98, b = -19\degree 36$) whose peak temperatures are 62.6 K and 55.5 K, respectively. The Orion A molecular cloud can be divided into three physically different regions: the main ridge, the extended component, and northern clumps. The main ridge is a major component of the Orion A cloud including Integral Shaped Filament (ISF; Bally et al. 1987), L1641, and other star forming sites. The main ridge consists of a number of clumps, filaments (Bally et al. 1987; Nagahama et al. 1998; Nakamura et al. 2012), and shells (Heyer et al. 1992; Nakamura et al. 2012) and most of the structures are also observed in the present
survey. One of the noticeable features in the main ridge is the existence of the gradient of some physical parameters including the line center velocity (e.g., Maddalena et al. 1986), volume density (Sakamoto et al. 1994), excitation temperature, and filament width (Nagahama et al. 1998), which we will discuss in the following subsections (§3.3.2, §3.3.3). Another striking feature is the well-defined boundary observed on the western side of the main ridge. This feature is observed by Wilson et al. (2005) with a 9’ resolution and they suggested the boundary is due to the stellar wind and/or radiation from the Orion OB1 association or ancient interaction with supernovae. The extended component (EC; Sakamoto et al. 1997) is located in the eastern side of the main ridge with the less intense emission typically < 15 K km s\(^{-1}\) in the integrated intensity map of \(^{12}\)CO\((J = 2–1)\). Molecular gas of the EC has observed only at a coarse angular resolution (Wilson et al. 2005), or toward small regions (Sakamoto et al. 1997). Sakamoto et al. (1997) proposed that the EC is located in front of the main ridge, and it was formed as a result of the interaction between the galactic atomic gas and the dense molecular gas in the main ridge. In the present survey, we covered the entire extent of the EC at the higher angular resolution. We detected a dozen of clumps which have relatively high intensity and well-defined boundary toward the EC region (hereafter "EC clumps"). The remarkable feature of the northern clumps are the lack of diffuse emission probably due to the interaction with the surrounding OB associations.

The Orion B molecular cloud is located in the upper-right side in the Figure 3.1. The maximum intensity of \(^{12}\)CO\((J = 2–1)\) is observed toward NGC2068 \((l = 205^\circ 37, b = -14^\circ 33)\) with a peak temperature of 31.9 K and that of \(^{12}\)CO\((J = 1–0)\) is observed toward NGC2023 \((l = 206^\circ 87, b = -16^\circ 53)\) with a peak temperature of 35.4 K. The Orion B molecular cloud can be divided into three regions: the southern part including NGC2023 and NGC2024 (hereafter, we call this part Southern cloud), the northern part including NGC2068 and NGC2071 (hereafter, Northern cloud), and the central part which has only diffuse extended emission (hereafter, 2nd component). The Southern cloud and the Northern cloud have clear boundary in the direction of the Orion OB1 association, which may be due to the stellar wind and/or radiation from massive stars. The 2nd component has a different velocity component from the Northern and Southern clouds, and thus it seems to have no physical relation to other clouds (Maddalena et al. 1986).
Figure 3.3: Integrated intensity maps of (a) $^{13}\text{CO}(J = 2–1)$ with peak intensity of 68 K km s$^{-1}$ and (b) $^{13}\text{CO}(J = 1–0)$ with peak intensity of 48 K km s$^{-1}$ toward the Orion A and B molecular clouds. The velocity range used for the integration is $0 < V_{\text{LSR}} < 20$ km s$^{-1}$ for both of the maps. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
13CO($J = 2–1$) and 13CO($J = 1–0$)

Figure 3.3 shows velocity-integrated intensity maps of 13CO($J = 2–1$) and 13CO($J = 1–0$). In general, both the $J = 2–1$ and $J = 1–0$ lines have similar spatial distributions except for the lower intensity region around the main ridge. The 13CO emission is detected toward the region where 12CO emission is relatively strong. However, the 13CO($J = 2–1$) emission is not detected in the regions toward with extended week 12CO emission. In the Orion A, the maximum intensity of 13CO($J = 2–1$) is observed toward Orion KL with a peak temperature of 17.4 K and that of 13CO($J = 1–0$) is observed toward 10' north to Orion KL ($l = 208°80, b = −19°27$) with a peak temperature of 12.8 K. The main ridge exhibits more filamentary shape than the 12CO distributions, which is considered to reflect the inner structure of the clouds due to its smaller optical depth. The main ridge has almost constant intensity (∼10 K km s$^{-1}$) expect for the local peaks around the L1641N ($l = 210°1, b = −19°6$). The helix shaped structure is seen in the southern side of the main ridge between $l = 211°$ and 213°, representing the possible influence of the magnetic field (?). The main ridge has well-defined boundary on both the western and eastern side of the filament. The diffuse emission is not seen toward the EC region in the $J = 2–1$ emission, while some of the EC clumps are clearly detected. In the northern clumps region, 13CO is observed where 12CO is relatively strong. In the Orion B, the maximum intensity of 13CO($J = 2–1$) is observed toward NGC2024 ($l = 206°57, b = −16°37$) with a peak temperature of 16.7 K and that of 13CO($J = 1–0$) is observed toward NGC2023 ($l = 206°87, b = −16°60$) with a peak temperature of 14.4 K. In the $J = 2–1$ emission, the Southern cloud and the Northern cloud are clearly separated. The clouds have well-defined boundary toward the western direction while some diffuse components are extended toward the opposite direction.

C$^{18}$O($J = 2–1$) and C$^{18}$O($J = 1–0$)

Figure 3.4 shows velocity integrated intensity maps of C$^{18}$O($J = 2–1$) and C$^{18}$O($J = 1–0$). In the Orion A, the maximum intensity of $J = 2–1$ is observed toward 14' north to Orion KL ($l = 208°78, b = −19°23$) with a peak temperature of 3.3 K, and that of $J = 1–0$ is observed toward L1641S ($l = 212°10, b = −19°17$) with a peak temperature of 2.8 K. In the Orion B, the maximum intensities of $J = 2–1$ and $J = 1–0$ are observed toward NGC2023 ($l = 206°87, b = −16°57$) with peak temperatures of 3.8 K and 3.6 K, respectively. The C$^{18}$O emission is detected where the 13CO emission is strong including main ridge of the Orion A and NGC2023, NGC2024,
3.3. RESULTS

Figure 3.4: Integrated intensity maps of (a) $^{18}$O($J = 2$–$1$) with peak intensity of 7.7 K km s$^{-1}$ and (b) $^{18}$O($J = 1$–$0$) with peak intensity of 8.0 K km s$^{-1}$ toward the Orion A and B molecular clouds. The velocity range used for the integration is $0 < V_{\text{LSR}} < 20$ km s$^{-1}$ for both of the maps. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
NGC2068, and NGC2071. The fact that most of the C$^{18}$O($J = 2–1$) emissions have higher intensity than C$^{18}$O($J = 1–0$) indicates that the region traced by C$^{18}$O has a temperature and density high enough to excite the molecule to the $J = 2$ state, and also that the lines are optically thin. The distribution of C$^{18}$O($J = 2–1$) emission is similar to the distribution of CS (Lada et al. 1991; Tatematsu et al. 1993) emission, which implies C$^{18}$O($J = 2–1$) traces a high density region with $n$(H$_2$) $\sim 10^4$ in the cloud.

3.3.2 Velocity structure

Velocity structures are very complicated in the Orion molecular cloud complex as seen in the velocity channel maps shown in Figure 3.5 and 3.6. In the Orion A, the main ridge seems to consist of two giant filaments: one is located at $l = 214^\circ–211^\circ$ in the velocity range $v_{\text{LSR}} = 1.0–7.0$ km s$^{-1}$, and the other is located at $l = 212^\circ–208^\circ$ in the velocity range $v_{\text{LSR}} = 7.0–13.0$ km s$^{-1}$. Both of the filaments consist of many smaller filaments, clumps, and shell-like structures. The helical filament observed in the velocity range $v_{\text{LSR}} = 10.0–11.5$ km s$^{-1}$ is the Orion east filament (Wilson et al. 2005) which has no physical relation to the Orion main cloud. The EC is detected at the velocity $v_{\text{LSR}} = 5.5–8.5$ km s$^{-1}$. One of the striking features is that the EC consists of many small scale structures (e.g., filaments and clumps) with weak intensities typically < 5 K in the $^{12}$CO($J = 2–1$) emission. The EC clumps have clearly different velocity from the EC which are $v_{\text{LSR}} > 8.5$ km s$^{-1}$ with relatively higher intensities typically > 5 K in the $^{12}$CO($J = 2–1$) and well-defined boundary. The Northern clumps are detected in the velocity $v_{\text{LSR}} = 10.0–16.0$ km s$^{-1}$. The Northern clumps consist of many small clumps. There are mainly two velocity components in the Orion B cloud: the lower velocity component corresponding to the 2nd component is found in the velocity range $v_{\text{LSR}} = 1.0–7.0$ km s$^{-1}$, and the higher velocity component corresponding to the Northern cloud and the Southern cloud is found in the velocity range $v_{\text{LSR}} = 7.0–16.0$ km s$^{-1}$. The lower velocity component seems to consist of shells, filaments, and clumps as found for the EC in the Orion A. On the other hand, the higher velocity component is not very filamentary structure compared with the main ridge in the Orion A. At the velocity $v_{\text{LSR}} > 13.0$ km s$^{-1}$, both of the Orion A and B clouds consist of many small clumps.

Figure 3.7 shows the intensity-weighted mean velocity maps. The $^{12}$CO and $^{13}$CO maps exhibit quite similar velocity distribution. In the Orion A, the main ridge has a velocity gradient while the EC has no velocity change. The Orion east filament is seen as the high velocity components in the north-east side around $l = 212^\circ–216^\circ$ of
Figure 3.5: $^{12}\text{CO}(J = 2-1)$ velocity channel maps for the velocity range $-0.5 < V_{\text{LSR}} < 17.5$ km s$^{-1}$ made at every 1.5 km s$^{-1}$. The start velocity for the integration is indicated in the top-left corner of each panel. The moment masked cube was used (see, §3.2).
Figure 3.6: Same as Figure 3.5, but for $^{13}\text{CO}(J = 2–1)$. 
3.3. RESULTS

Figure 3.7: Intensity-weighted mean velocity map in a velocity range from 0 to 20 km s$^{-1}$ for (a) $^{12}$CO($J = 2-1$),
(b) $^{13}$CO($J = 2-1$), and (c) C$^{18}$O($J = 2-1$).
Figure 3.8: Line width map of (a) $^{12}$CO ($J = 2-1$), (b) $^{13}$CO ($J = 2-1$), and (c) C$^{18}$O ($J = 2-1$). The line widths are obtained by dividing integrated intensity by peak temperature.
the Orion A. In the Orion B, it is clear that the cloud consists of mainly two different velocity components also as seen in Figure 3.5.

The line width maps obtained by dividing the integrated intensity by the peak temperature are shown in Figure 3.8. In the Orion A, the line width increases as approaching to the center of the main ridge and as approaching to the Orion KL. This tendency is more clearly seen in $^{13}$CO. The EC has small line width typically of $<2$ km s$^{-1}$. In the case of the Orion B cloud, $^{12}$CO emission lines with a very large line width are widely seen, which is explained mainly due to a mixture of some distinct velocity components. The $^{13}$CO map seems to trace the velocity structure of the main component of the Orion B as the emission line is optically thinner. In $^{13}$CO, the largest velocity width in the Southern cloud and the Northern cloud are seen toward the NGC2024 and the NGC2071, respectively.

Figure 3.9 shows the longitude-velocity diagrams. The velocity gradient of the Orion A is also clearly seen in this figure. It seems to have velocity gradient along longitude also in the Orion B. The velocity gradients are calculated as $0.15$ and $-0.08$ km s$^{-1}$ pc$^{-1}$, for the Orion A and the Orion B, respectively. The 2nd component of the Orion B is clearly seen around at $v_{LSR} = 5$ km s$^{-1}$. The EC of Orion A cannot be identified clearly in the longitude-velocity diagram, because it has the same velocity as the main ridge.

Figure 3.10 shows velocity-latitude diagrams. In the figure, both of the Orion A and B clouds have no velocity gradient. There is clear boundary between the Orion A and B molecular cloud around $b = -17^\circ$. In the Orion A, the EC is clearly seen in the velocity around 5 km s$^{-1}$ and the EC clumps are seen with a velocity around 10 km s$^{-1}$. The extended component of the Orion B is also clearly seen in the velocity-latitude diagram around at $v_{LSR} = 5$ km s$^{-1}$.

### 3.3.3 Line ratios

In this subsection, we derive the intensity ratios of the observed molecular lines to investigate the physical properties of the molecular gas. We should note that we calculate the ratios without matching the angular resolutions. Both of the $J = 2$–$1$ and $J = 1$–$0$ data were originally observed at an angular resolution of $\sim 2'$7. However, because the observations by the 1.85-m telescope were carried out in the OTF mode, the resultant angular resolution for the $J = 2$–$1$ lines is lowered to $\sim 3'$4 as stated in Section 2. On the other hand, the $J = 1$–$0$ observations by the 4-m telescopes were made with an undersampling way, which makes it very difficult to smooth the data exactly to the same angular resolution as that of the $J = 2$–$1$ data.
Figure 3.9: Longitude-velocity (l-v) diagram of the Orion A and B molecular clouds for the emission of (a)$^{12}$CO($J = 2–1$), and (b)$^{13}$CO($J = 2–1$). We used spectra in the latitude range between $b = -21^\circ$ and $-13^\circ$ to produce the diagrams.
Figure 3.10: Velocity-latitude (v-b) diagram of the Orion A and B molecular clouds for the emission of (a) $^{12}$CO($J = 2–1$), and (b) $^{13}$CO($J = 2–1$). We used spectra in the longitude range between $l = 204^\circ$ and $216^\circ$ to produce the diagrams.
We, therefore, decided not to attempt to standardize the angular resolutions but to use all of the data as that are. If we observe a point source, the observed intensity would differ by a factor of $\sim 1.5$ due to the difference of the angular resolutions ($3^4$ or $2^7$). This is the maximum estimate for the possible error in the following analyses arising from the difference of the angular resolutions. The actual errors should be much smaller, because the CO emission lines are spatially extended as shown in the previous subsections. In this paper, we neglected all the pixels where the intensities of each line are lower than $3 \sigma$ noise level when deriving the line ratios.

**Intensity ratio of $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$)**

Figure 3.11 shows the distribution of the $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$) intensity ratio (hereafter, $R_{2-1/1-0}^{12}$). In general, the ratio gets close to unity if the emission is quite optically thick, and it reflects the excitation temperature of the region if they are optically thin. The overall tendency in the figure is similar to that of Sakamoto et al. (1994); the ratio is approximately unity along the main ridge of the clouds and decreases down to 0.5 in the peripheral regions. The present data reveal the ratio even in much lower intensity regions compared with Sakamoto et al. (1994) mainly because the present $J = 2–1$ observations are more sensitive.

The maximum ratios of $R_{2-1/1-0}^{12}$ are observed toward the cloud boundary near NGC1977 and the lower part of the main ridge around $l = 209^\circ–211^\circ$ for the Orion A. For the Orion B, the maximum ratios are observed toward the western side of the main cloud. In these regions, the ratio becomes higher than 1.5. The high ratio indicates that the $^{12}$CO lines are optically thin, and that the gas is dense and warm enough to excite to the $J = 2$ level. This suggests the interaction of the molecular clouds with the stellar winds and the radiation from the surrounding massive stars. Relatively high ratio ($\sim 1.3$) is observed near the Orion KL, indicating that the region is also affected by the star clusters in M42 including the Trapezium.

In the Orion A main ridge, a gradient of the ratio is observed, which is previously discovered with Sakamoto et al. (1994). The ratio has the local peaks near L1641N and L1641S which are well-known star forming regions associated with the shell-like structures (Heyer et al. 1992). The EC is observed as low ratio ($\sim 0.5$) while the ratio of the EC clumps are relatively high ($\sim 0.8$). The Northern clumps in the Orion A, the ratio is relatively high especially near the Orion KL. The ratio of the Orion B is relatively high ($\sim 0.8$) except for the 2nd component.
3.3. RESULTS

Figure 3.11: Distribution of the $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$) intensity ratio. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
CHAPTER 3. OBSERVATION OF THE ORION MOLECULAR CLOUDS

Intensity ratio of $^{13}$CO($J = 2–1$)/$^{13}$CO($J = 1–0$)

Figure 3.12 shows the distribution of the $^{13}$CO($J = 2–1$)/$^{13}$CO($J = 1–0$) intensity ratio (hereafter, $R_{13}^{2-1/1-0}$). This ratio reflects both the kinematic temperature and density of the gas because of the small optical depth of the $^{13}$CO emission lines. The large scale tendency is similar to that of the ratio of $^{12}$CO while the dynamic range is larger. The maximum ratio in the Orion A is observed toward the cloud boundary near the Orion KL with a ratio of $\sim 2$. The gradient seen in $R_{2-1/1-0}^{12}$ is seen also in $R_{2-1/1-0}^{13}$. We found that the ratio is $\sim 0.8$ in the region near L1641N and is 0.3–0.5 in the region at $l > 211.5^\circ$. Some of the EC clumps and the Northern clumps are detected with the ratio of $\sim 0.8$. In the Orion B clouds, the maximum ratio ($> 1.5$) is observed in the western side of NGC2024. Other clouds in the Orion B observed to be relatively high ratio of $\sim 0.9$.

Intensity ratio of $^{13}$CO($J = 2–1$)/$^{12}$CO($J = 2–1$)

Figure 3.13 shows the distribution of the $^{13}$CO($J = 2–1$)/$^{12}$CO($J = 2–1$) intensity ratio (hereafter, $R_{13/12}^{2-1}$). The ratio roughly reflects the column density when the excitation temperatures are the same for both of the lines. Due to the photon trapping effect, the ratio is also sensitive to local density where the $^{13}$CO($J = 2–1$) is sub-thermally excited and the $^{12}$CO($J = 2–1$) is optically thick. The ratio is also affected by the abundance variation which mainly reflects the intensity of the interstellar radiation field in the massive star forming region (e.g., Ripple et al. 2013). The distribution of $R_{2-1}^{13/12}$ is somewhat different from the intensity distributions of the $^{13}$CO($J = 2–1$) and also of $^{12}$CO($J = 2–1$). In Orion A, the ratio is nearly constant from the north to south all along $b \sim -19^\circ 5$, although the intensity distribution of $^{13}$CO($J = 2–1$) and $^{12}$CO($J = 2–1$) are strongest at the northern edge, decreasing to the southern edge. In Orion B, the ratio is stronger around the Northern cloud than the Southern cloud, although the tendency is opposite to the intensity distribution of $^{13}$CO($J = 2–1$) and $^{12}$CO($J = 2–1$).

3.4 Analyses

3.4.1 Deriving column densities and masses

Column densities of the molecular gas are often derived by assuming the X-factor, which is a conversion factor from line intensities to column densities for optically thick
Figure 3.12: Distribution of the $^{13}$CO($J = 2–1$)/$^{13}$CO($J = 1–0$) intensity ratio. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
Figure 3.13: Distribution of the $^{13}\text{CO}(J = 2–1)/^{12}\text{CO}(J = 2–1)$ intensity ratio. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
lines, and by assuming the Local Thermodynamic Equilibrium (LTE) for optically thin lines. In this subsection, we derive the column densities and the masses by using the assumptions in the above, and discuss the cause of their differences. In order to investigate the difference depending on the environments in terms of the star formation activity, we divide the observed area into four regions, i.e., Orion A-1, Orion A-2, Orion B-1, and Orion B-2 (see Figure 3.2). Orion A-1 is a part of Orion A at $l > 211^\circ$, and it includes no massive star formation site. Orion A-2 is the region at $l < 211^\circ$ where the massive star formation is taking place. Orion B-1 is a part of Orion B at $b < 15^\circ$ corresponding to the Southern cloud as introduced in §3.3.1, and Orion B-2 is the region at $b > 15^\circ$ corresponding to the Northern cloud.

**Line luminosities**

We summarize the luminosity of the observed emission lines and their ratios in Table 3.1. To derive the intensity, we integrated the observed emission lines over the surface areas of each subregion. The ratio of $J = 2–1/J = 1–0$ is different depending on the isotopes. The $R_{12}^{18}$ is the highest $\sim 0.6–0.9$ and the $R_{12}^{18}$ is the lowest $\sim 0.1–0.7$. Especially in the A1 subregion, $R_{12}^{18}$ is very low compared with $R_{12}^{12}$ by a factor of 3. The ratios of $^{13}\text{CO}/^{12}\text{CO}$ show similar tendency both in $J = 2–1$ and $J = 1–0$. The A2 subregion is higher than the A1 subregion and the B2 subregion is higher than the B1 subregion.
Table 3.1: Observed line luminosities and luminosity ratios

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<th>( L_{2-1}^{18} )</th>
<th>( L_{1-0}^{12} )</th>
<th>( L_{1-0}^{13} )</th>
<th>( L_{1-0}^{18} )</th>
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<th>( R_{2-1/1-0}^{18} )</th>
<th>( R_{1-0}^{13/12} )</th>
<th>( R_{1-0}^{18/12} )</th>
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<td>2930</td>
<td>88</td>
<td>29500</td>
<td>4420</td>
<td>158</td>
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<td>0.56</td>
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<td>0.48</td>
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<td>413</td>
<td>3</td>
<td>6950</td>
<td>954</td>
<td>28</td>
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<td>0.43</td>
<td>0.13</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
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<td>0.61</td>
<td>0.14</td>
<td>0.16</td>
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<tr>
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<td>10500</td>
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<td>0.13</td>
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Col. (1): Source name.
Cols. (2)–(4): Total luminosity of the \(^{12}\text{CO}, ^{13}\text{CO}, \) and \(^{18}\text{O}(J = 2–1)\), respectively in K km s\(^{-1}\) pc\(^2\).
Cols. (5)–(7): Total luminosity of the \(^{12}\text{CO}, ^{13}\text{CO}, \) and \(^{18}\text{O}(J = 1–0)\), respectively in K km s\(^{-1}\) pc\(^2\).
Cols. (8)–(12): Luminosity ratios of the \( R_{2-1/1-0}^{12} = L_{2-1}^{12}/L_{1-0}^{12}, \) \( R_{2-1/1-0}^{13} = L_{2-1}^{13}/L_{1-0}^{13}, \) \( R_{2-1/1-0}^{18} = L_{2-1}^{18}/L_{1-0}^{18}, \) \( R_{1-0}^{13/12} = L_{1-0}^{13}/L_{1-0}^{12}, \) and \( R_{1-0}^{18/12} = L_{1-0}^{18}/L_{1-0}^{12}, \) respectively.
Table 3.2: Averaged column densities and column density ratios

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<th>$N_{LTE}^{18,2-1}$</th>
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<tr>
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<td>24.3</td>
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<td>0.83</td>
<td>57.2</td>
<td>39.6</td>
<td>1.43</td>
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Col. (1): Source name.
Cols. (2): Averaged column density of the $H_2$ derived from $^{12}$CO($J = 1-0$) in $10^{20}$ cm$^{-2}$.
Cols. (3) and (4): Averaged column density of the $H_2$ derived from $^{13}$CO($J = 2-1$) and $^{13}$CO($J = 1-0$), respectively in $10^{20}$ cm$^{-2}$.
Col. (5): Column density ratio of $R_{13/12}^N = N_{LTE}^{13,1-0}/N_X^{1-0}$.
Col. (6): Column density ratio of $R_{LTE,13}^N = N_{LTE}^{13,2-1}/N_{LTE}^{13,1-0}$.
Cols. (7) and (8): Averaged column density of the $H_2$ derived from C$^{18}$O($J = 2-1$) and C$^{18}$O($J = 1-0$), respectively in cm$^{-2}$.
Col. (9): Column density ratio of $R_{18/12}^N = N_{LTE}^{18,1-0}/N_X^{1-0}$.
Col. (10): Column density ratio of $R_{LTE,18}^N = N_{LTE}^{18,2-1}/N_{LTE}^{18,1-0}$. 
### Table 3.3: Total masses and mass ratios

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<th>( M_{13}^{\text{LTE}} )</th>
<th>( M_{13}^{\text{LTE},13} )</th>
<th>( R_{13}^{M} )</th>
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</tr>
<tr>
<td>A</td>
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</tr>
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<td>18.2</td>
<td>0.76</td>
<td>1.4</td>
<td>1.0</td>
<td>0.37</td>
<td>9.0</td>
<td>0.37</td>
<td>0.16</td>
</tr>
<tr>
<td>A1</td>
<td>25.8</td>
<td>17.5</td>
<td>3.8</td>
<td>0.71</td>
<td>0.21</td>
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<td>0.34</td>
<td>9.0</td>
<td>0.37</td>
<td>0.16</td>
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<td>10.7</td>
<td>0.77</td>
<td>2.6</td>
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<td>0.33</td>
<td>19.2</td>
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<td>0.19</td>
</tr>
<tr>
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<td>24.0</td>
<td>18.2</td>
<td>6.7</td>
<td>0.76</td>
<td>1.4</td>
<td>1.0</td>
<td>0.37</td>
<td>9.0</td>
<td>0.37</td>
<td>0.16</td>
</tr>
<tr>
<td>B2</td>
<td>14.2</td>
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<td>4.0</td>
<td>0.88</td>
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<td>1.0</td>
<td>0.32</td>
<td>8.2</td>
<td>0.58</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Col. (1): Source name.
Col. (2): Total molecular cloud mass derived from \( ^{12}\text{CO}(J = 1-0) \) in \( 10^3 M_\odot \).
Col. (3) and (4): Total molecular cloud mass derived from \( ^{13}\text{CO}(J = 2-1) \) and \( ^{13}\text{CO}(J = 1-0) \), respectively in \( 10^3 M_\odot \).
Col. (5): Mass ratio of \( R_{13}^{M} = M_{13}^{\text{LTE}} / M_{13}^{\text{LTE},13} \).
Col. (6): Mass ratio of \( R_{18}^{M} = M_{18}^{\text{LTE}} / M_{18}^{\text{LTE},18} \).
Col. (7) and (8): Total molecular cloud mass derived from \( ^{18}\text{O}(J = 2-1) \) and \( ^{18}\text{O}(J = 1-0) \), respectively in \( 10^3 M_\odot \).
Column densities

The X-factor, which converts from $^{12}\text{CO}(J = 1–0)$ line intensities to the column densities of molecular hydrogen, has been derived by comparing the intensities with other tracers of mass, such as virial masses (e.g., Solomon et al. 1987), proton masses from gamma-ray observations (e.g., Bloemen et al. 1986), and dust observations (e.g., Dame et al. 2001). For the Galactic clouds, the X-factor is derived to be approximately $1.8 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s (Dame et al. 2001), and we use this value in this paper. The averaged column densities derived with the X-factor is $N_{X}^{1–0} (\text{H}_2) = 18.9 \times 10^{20}$ cm$^{-2}$. We also derived the averaged column densities for each subregion and summarized them in Table 3.2.

$J = 1–0$ transition of the $^{13}\text{CO}$ and $^{18}\text{O}$ have been often used to derive the column density under the assumption of the LTE (e.g., Dickman 1978; Pineda et al. 2010), because the Einstein’s A coefficient is small, and thus the critical density for the excitation is low. The $J = 2–1$ transitions have higher critical densities for the excitation, and they can be sub-thermally excited in lower-density regions. In the analyses, we apply the LTE assumption for all of the transition lines, and discuss the cause of the differences of the derived properties. Furthermore, we use the peak brightness temperature of each $^{12}\text{CO}$ transition line for the estimation of the excitation temperature of the $^{13}\text{CO}$ and $^{18}\text{O}$ transitions. Assuming the LTE, the excitation temperature $T_{\text{ex}}$ is derived from the peak brightness temperature of $^{12}\text{CO}$ line, $T_{\text{peak}}$, as

$$T_{\text{ex}}^{1–0} = 5.53 \left\{ \ln \left[ 1 + \frac{5.53}{T_{\text{peak}}^{12,1–0} + 0.84} \right] \right\}^{-1}$$

$$T_{\text{ex}}^{2–1} = 11.06 \left\{ \ln \left[ 1 + \frac{11.06}{T_{\text{peak}}^{12,2–1} + 0.19} \right] \right\}^{-1}.$$  

Using the excitation temperature, the optical depths of the $^{13}\text{CO}$ and $^{18}\text{O}$ emissions lines are derived from the brightness temperature, $T_{\text{mb}}(v)$,

$$\tau_{J=1}^{13}(v) = -\ln \left\{ 1 - \frac{T_{\text{mb}}^{13,1–0}(v)}{5.29} \left[ \frac{1}{\exp(5.29/T_{\text{ex}}) - 1} - 0.17 \right]^{-1} \right\}$$

$$\tau_{J=1}^{18}(v) = -\ln \left\{ 1 - \frac{T_{\text{mb}}^{18,1–0}(v)}{5.27} \left[ \frac{1}{\exp(5.27/T_{\text{ex}}) - 1} - 0.17 \right]^{-1} \right\}$$
The column densities of $^{13}$CO and C$^{18}$O in the upper state, $N_u$, are derived by the following equations,

$$N^{13}_{J=1} = 1.98 \times 10^{16} \left[ \exp \left( \frac{5.29}{T_{\text{ex}}} \right) - 1 \right]^{-1} \int \tau^{13}_{J=1}(v)dv$$

$$N^{18}_{J=1} = 1.97 \times 10^{16} \left[ \exp \left( \frac{5.27}{T_{\text{ex}}} \right) - 1 \right]^{-1} \int \tau^{18}_{J=1}(v)dv$$

$$N^{13}_{J=2} = 1.65 \times 10^{16} \left[ \exp \left( \frac{10.58}{T_{\text{ex}}} \right) - 1 \right]^{-1} \int \tau^{13}_{J=2}(v)dv$$

$$N^{18}_{J=2} = 1.64 \times 10^{16} \left[ \exp \left( \frac{10.54}{T_{\text{ex}}} \right) - 1 \right]^{-1} \int \tau^{18}_{J=2}(v)dv.$$  (3.10)

Assuming the LTE, the column density of the rotational state of $J$ is related to the total CO column density as

$$N_{\text{total}}(\text{CO}) = N_J \frac{Z}{2J+1} \exp \left[ \frac{hB_0J(J+1)}{kT_{\text{ex}}} \right]$$  (3.11)

where $B_0$ is the rotational constant of the CO isotopologues, $B_0 = 5.51 \times 10^{10}$ s$^{-1}$ and $5.49 \times 10^{10}$ s$^{-1}$ for $^{13}$CO and C$^{18}$O, respectively. $Z$ is the partition function which is given by

$$Z = \sum_{J=0}^{\infty} (2J+1) \exp \left[ - \frac{hB_0J(J+1)}{kT_{\text{ex}}} \right].$$  (3.12)

The column density of the molecular gas, $N(\text{H}_2)$, is derived by

$$N(\text{H}_2) = X N_{\text{total}}(\text{CO})$$  (3.13)

where $X$ is the isotopic abundance ratio of the CO isotopologues relative to H$_2$. We adopt $X[^{13}\text{CO}] = 7.1 \times 10^5$ and $X[\text{C}^{18}\text{O}] = 5.9 \times 10^6$ (Frerking et al. 1982).

The derived averaged column densities over the whole observed area from $^{13}$CO and C$^{18}$O of $J = 2–1$ and $J = 1–0$ are $N_{\text{LTE}}^{13,2-1} = 20.7 \times 10^{20}$ cm$^{-2}$, $N_{\text{LTE}}^{13,1-0} = 22.4 \times 10^{20}$ cm$^{-2}$. The derived averaged column densities for the CO isotopologues in the upper state, $N_u$, are obtained by integrating the fraction of the line of sight from which the photons escape.
The column densities derived from $^{12}\text{CO}$ are similar to that of $^{13}\text{CO}$ while the C$^{18}\text{O}$ show significant higher averaged column densities. This indicates the C$^{18}\text{O}$ emission traces higher column density region than $^{12}\text{CO}$ and $^{13}\text{CO}$, probably due to the photodissociation and chemical fractionation of the species (e.g., Warin et al. 1996). Another possibility is that the abundance ratio of C$^{18}\text{O}$ in the Orion region is different from those in the other regions measured by Frerking et al. (1982).

**Masses**

The gas mass is calculated from the molecular gas column densities by

$$
\left( \frac{M_{\text{gas}}}{M_\odot} \right) = 4.05 \times 10^{-1} \mu_{\text{H}_2} \left( \frac{m_{\text{H}}}{\text{kg}} \right) \left( \frac{d}{\text{pc}} \right)^2 \left( \frac{\Delta l}{\text{arcmin}} \right) \left( \frac{\Delta b}{\text{arcmin}} \right) \left( \frac{N(\text{H}_2)}{\text{cm}^{-2}} \right)
$$

(3.14)

where $\mu_{\text{H}_2} \sim 2.7$ is the mean molecular weight per H$_2$ molecule, $m_{\text{H}}$ is the atomic hydrogen mass, $d$ is the distance, and $\Delta l$ and $\Delta b$ are the pixel size along the galactic coordinates.

The derived gas masses are summarized in Table 3.3. The masses derived from the $J = 1–0$ are larger than those derived from the $J = 2–1$ in all the CO isotopes. The total gas masses derived from $^{13}\text{CO}(J = 1–0)$ for four regions are about 70–80% of those derived from $^{12}\text{CO}(J = 1–0)$ luminosities. The ratio of the total masses derived from the two molecular lines are almost uniform not depending on the regions. This implies that the optically thick $^{12}\text{CO}(J = 1–0)$ line is well proportional to the total mass, and if we assume that the mass derived from $^{13}\text{CO}(J = 1–0)$ traces the true total mass more reliably, the X factor for $^{12}\text{CO}(J = 1–0)$ intensity is estimated to be $1.5 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$. The mass derived from $^{13}\text{CO}(J = 2–1)$ is lower than that from $^{13}\text{CO}(J = 1–0)$ by a factor of about 3, indicating that the $J = 2–1$ line is sub-thermally excited. Especially toward the A1 subregion, the ratio $^{13}\text{CO}(J = 2–1)$...
2–1)/^{13}\text{CO}(J = 1–0) is lower than the other regions by a factor of 1.4. This indicates that the density of the Orion A1 region is lower than other two regions, which is also discussed in the previous sub-subsection.

3.4.2 Large velocity gradient analysis

Molecular lines with different critical densities for the excitation can be used to estimate the density and the temperature of the emitting region. For the optically thick molecular lines, we need to include an effect of photon trapping. The photon trapping varies the excitation state and depends on the morphology of the cloud. For simplicity, we used the large velocity gradient (LVG) approximation method (e.g., Goldreich & Kwan 1974; Scoville & Solomon 1974), which assumes a spherically symmetric cloud of uniform density and temperature with a spherically symmetric velocity distribution proportional to the radius and uses a Castor escape probability formalism (Castor 1970). It solves the equations of statistical equilibrium for the fractional population of CO rotational levels at each density and temperature by incorporating the photon escape probability that is effective in the optically thick case. The widely used radiative transfer code RADEX also uses the same technique with an ability to choose three different formulations of the escape probability (van der Tak et al. 2007). In the non-LTE analyses, intensities of a few lines are compared and used to determine the physical properties of the gas where lines are emitted. Therefore, the analyses is sensitive to the density similar to the critical densities of the used lines (e.g., Castets et al. 1990; Beuther et al. 2000; Zhu et al. 2003). The selection of the lines for the non-LTE analyses is important. Recently, the combination of optically thin and thick lines with different transitions are found to be good tracers of the physical properties of the gas and the derived physical properties well reflect the star formation activities and the surrounding environments (e.g., Martin et al. 2004; Nagai et al. 2007; Mizuno et al. 2010; Minamidani et al. 2011; Torii et al. 2011; Peng et al. 2012; Fukui et al. 2014). In this paper, we use the $^{12}\text{CO}(J=2–1)$, $^{13}\text{CO}(J=2–1)$, and $^{13}\text{CO}(J=1–0)$ lines with the single component LVG analyses.

Our analysis includes the lowest 40 rotational levels of the ground vibrational level and uses Einstein A coefficient and ortho/para H$_2$ impact rate coefficients of ?. The ratio of ortho- to para-H$_2$ molecules is calculated by assuming the thermal equilibrium state. We performed the calculations for a $^{12}\text{CO}$ fractional abundance of $X(^{12}\text{CO}) = [^{12}\text{CO}]/[\text{H}_2] = 1 \times 10^{-4}$ and a $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio of 71 (Frerking et al. 1982). Another parameter we need for the calculation is the velocity gradient often described as $dv/dr$. Figure 3.14 shows contour plots of the LVG analysis by
Figure 3.14: Contour plots of the calculated line intensity ratio using the LVG analyses. Contours are the values of (a) $R^{13}_{2-1/1-0}$, (b) $R^{13/12}_{2-1}$, and (c) $R^{13}_{2-1/1-0}$ and $R^{13/12}_{2-1}$. We assumed, $X^{(12)CO} = 1 \times 10^{-4}$, $dv/dr = 1.0 \text{ km s}^{-1} \text{ pc}^{-1}$, and the abundance ratio of $^{12}\text{CO}/^{13}\text{CO} = 71$.

assuming $dv/dr$ to be $1 \text{ km s}^{-1} \text{ pc}^{-1}$ which are derived from the typical line width and the size of the cloud. Solid and dashed lines show contours of $R^{13}_{2-1/1-0}$ and $R^{13/12}_{2-1}$ ratios, respectively. The figure indicates that the $R^{13/12}_{2-1}$ ratio basically depends on the density, and the $R^{13}_{2-1/1-0}$ ratio depends on both of the density and temperature. The $R^{13/12}_{2-1}$ dependency comes from the facts that it reflects the optical depth of $^{13}\text{CO}(J = 2-1)$ when $^{12}\text{CO}(J = 2-1)$ is optically thick, and also that less $\text{H}_2$ density is needed for the collisional excitation of $^{12}\text{CO}(J = 2-1)$ than the optically thin $^{13}\text{CO}(J = 2-1)$ line due to the photon trapping effect of the $^{12}\text{CO}(J = 2-1)$ line. The $R^{13}_{2-1/1-0}$ is only dependent on the temperature if both of the lines are optically thin and fully thermalized. This ratio also depends on the density in terms of the different critical density for the excitation. Roughly speaking, $R^{13/12}_{2-1}$ traces the density, and $R^{13}_{2-1/1-0}$ is larger for higher temperature and density. Because these two ratios have different dependence on the density and temperature, we are able to estimate the density and temperature from the intersection in the figure.

Deriving physical parameters

First, we chose 7 different points which have different environments for calculating the physical properties with the LVG analysis. Orion KL is an example of a region of high temperature (Figure 3.15). This region has a high $R^{13}_{2-1/1-0}$ and low $R^{13/12}_{2-1}$. The
Table 3.4: Results of LVG analyses

<table>
<thead>
<tr>
<th>Source</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$T_{2-1}^{12}$ (K)</th>
<th>$T_{2-1}^{13}$ (K)</th>
<th>$T_{1-0}^{13}$ (K)</th>
<th>$R_{2-1}^{13/12}$</th>
<th>$R_{2-1/1-0}^{13}$</th>
<th>$T_{\text{kin}}$ (K)</th>
<th>$n$(H$_2$) (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion KL</td>
<td>209.00</td>
<td>-19.40</td>
<td>57.8</td>
<td>15.6</td>
<td>10.1</td>
<td>0.27</td>
<td>1.54</td>
<td>88</td>
<td>1800</td>
</tr>
<tr>
<td>OMC-3</td>
<td>208.60</td>
<td>-19.20</td>
<td>23.8</td>
<td>12.2</td>
<td>10.9</td>
<td>0.51</td>
<td>1.12</td>
<td>34</td>
<td>2200</td>
</tr>
<tr>
<td>L1641-N</td>
<td>210.07</td>
<td>-19.67</td>
<td>19.2</td>
<td>5.8</td>
<td>7.7</td>
<td>0.30</td>
<td>0.76</td>
<td>21</td>
<td>1300</td>
</tr>
<tr>
<td>L1641-S</td>
<td>212.00</td>
<td>-19.33</td>
<td>6.8</td>
<td>2.1</td>
<td>4.1</td>
<td>0.31</td>
<td>0.51</td>
<td>10</td>
<td>1000</td>
</tr>
<tr>
<td>NGC2024</td>
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<td>-16.33</td>
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<td>0.67</td>
<td>0.93</td>
<td>30</td>
<td>2200</td>
</tr>
<tr>
<td>NGC2023</td>
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<td>30.2</td>
<td>12.8</td>
<td>13.9</td>
<td>0.43</td>
<td>0.92</td>
<td>33</td>
<td>2000</td>
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<td>25.6</td>
<td>12.5</td>
<td>14.2</td>
<td>0.49</td>
<td>0.88</td>
<td>26</td>
<td>1600</td>
</tr>
<tr>
<td>NGC2071</td>
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<td>14.3</td>
<td>6.8</td>
<td>9.6</td>
<td>0.48</td>
<td>0.71</td>
<td>30</td>
<td>1400</td>
</tr>
</tbody>
</table>

Figure 3.15: (left)Contour plots of the LVG analyses of the Orion KL region with $Xdr/dv = 1.0 \times 10^{-4}$ pc km$^{-1}$ s. The vertical axis is kinetic temperature $T_{\text{kin}}$, and the horizontal axis is molecular hydrogen density $n$(H$_2$). Solid lines represent $R_{2-1/1-0}^{13}$, and dashed lines represent $R_{2-1}^{13/12}$ with intensity calibration errors of 10%. Gray scales show the results of $\chi^2$ test. (right)Spectra used for the LVG analyses. The dashed line represents $^{12}$CO($J = 2-1$), solid black line represents $^{13}$CO($J = 2-1$), and solid gray line represents $^{13}$CO($J = 1-0$). The $^{13}$CO are scaled up by a factor of 2.
Figure 3.16: Same as Figure 3.15, but for the OMC3 region.

Figure 3.17: Same as Figure 3.15, but for the L1641S region.
Table 3.5: Summary of molecular cloud properties

<table>
<thead>
<tr>
<th>Region / Subregion</th>
<th>$\langle N_{13-0}^{13}\rangle$ (10$^{20}$ cm$^{-2}$)</th>
<th>$M_{13-0}^{13}$ (10$^3$ M$_{\odot}$)</th>
<th>$T_{\text{kin}}$ (K)</th>
<th>$n(H_2)$ (cm$^{-3}$)</th>
<th>SFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>The entire Orion region</td>
<td>22.4</td>
<td>90</td>
<td>28.8</td>
<td>1000</td>
<td>0.037</td>
</tr>
<tr>
<td>The entire Orion A region</td>
<td>20.8</td>
<td>59</td>
<td>25.4</td>
<td>1000</td>
<td>0.045</td>
</tr>
<tr>
<td>A1</td>
<td>16.9</td>
<td>18</td>
<td>14.9</td>
<td>870</td>
<td>0.025</td>
</tr>
<tr>
<td>A2</td>
<td>23.2</td>
<td>41</td>
<td>31.8</td>
<td>1100</td>
<td>0.054</td>
</tr>
<tr>
<td>The entire Orion B region</td>
<td>26.4</td>
<td>30</td>
<td>35.8</td>
<td>1000</td>
<td>0.020</td>
</tr>
<tr>
<td>B1</td>
<td>28.4</td>
<td>18</td>
<td>44.7</td>
<td>990</td>
<td>0.018</td>
</tr>
<tr>
<td>B2</td>
<td>24.3</td>
<td>12</td>
<td>25.5</td>
<td>1000</td>
<td>0.023</td>
</tr>
</tbody>
</table>

analyzed curves are well crossed, and thus the temperature and the density are well determined to be 88 K and 1800 cm$^{-3}$, respectively. The density is well consistent with the values estimated by Castets et al. (1990) who determined to be a few 10$^3$ cm$^{-3}$. OMC-3 region is an example of a region of high-density and moderate-temperature (Figure 3.16). This region has a high $R_{13}^{13/12}$ with moderate $R_{13}^{13/12}$. The analyzed curves are also well crossed for this region, and the temperature and the density are determined to be 34 K and 2200 cm$^{-3}$, respectively. L1641S is an example of a region of low-density and low-temperature (Figure 3.17). This region has the low $R_{13}^{13/12}$ with low $R_{13}^{13/12}$. We determined the temperature and density to be 10 K and 1000 cm$^{-3}$, respectively. From these analyses, the temperature and density are successfully derived for the different environments. We also analyzed some other regions. Results are summarized in Table 3.4.

Spatial distribution of density and temperature

As we described in the previous subsection, the temperature and density of the molecular gas can be well determined by the LVG analyses in various environment. Thus, we apply this method to the whole observed pixels. Procedures we used are as follows: (1) we first generated the integrated intensity ratio maps of $R_{2-1}^{13/12}$ and $R_{2-1}^{13/12}$, and then (2) we calculated the line intensity for each density and temperature by using LVG analysis assuming uniform sphere structure and constant velocity gradient $(dv/dr = 1$ km s$^{-1}$ pc$^{-1}$). (3) We finally compared the observed line ratios and calculated intensity ratios to determine the physical properties of the molecular gas using $\chi^2$ test. Results of the analyses are shown in Figures 3.18 and 3.19 for the kinematic temperature and the density of the molecular gas, respectively.
Figure 3.18: Map of the gas kinetic temperature calculated by the LVG analyses. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
Figure 3.19: Map of the gas density calculated by the LVG analyses. The area indicated by the solid line denotes the field observed with the 1.85-m telescope.
The kinematic temperature is mostly in the range of 20 K to 50 K along the cloud ridge. The temperature tends to be high in the active star formation sites and decline to the peripheral regions. We found especially high temperature in some regions. One is the east of the Orion KL region near the Trapezium cluster. This region is considered to interact with the stellar wind and radiation from the Trapezium cluster. The western part of this region has no significant high temperature structures. Another region is the southern edge of the Orion B cloud which is located in a front of the OB1b subgroup. This region seems to be influenced by the radiation of old OB stars. We also note some other high temperature regions. One is found in the vicinity of L1641N. Actually this region has high temperature (~100 K) but not so large spacial extent as that of Orion KL. This suggests L1641N is more deeply embedded in the molecular gas. Another one is the south-west side of the main ridge of the Orion A. In this region, molecular gas is probably heated by the OB1b or 1c subgroups located southeast to the Orion A molecular cloud.

The densities derived with this analysis show values in the range of 500 to 5000 cm\(^{-3}\). The high density regions (~2000 cm\(^{-3}\)) are located in the north of Orion KL for the Orion A and in the south of the Southern cloud for the Orion B. In the Orion A, the main ridge has a density gradient decreasing toward the outer regions, as pointed out by Sakamoto et al. (1994). We can also find small scale density variations. For instance, there are local peaks around the L1641N and L1641S regions.

3.4.3 Distribution of YSOs

In this subsection, we compare the derived physical parameters of the gas with the star formation activities. In the Orion region, a new catalog of Young Stellar Objects (YSOs) was recently compiled out of the infrared survey using the Spitzer space telescope (Megeath et al. 2012) toward regions with high extinction, which we call Spitzer catalog. The cataloged YSOs have dusty disk or infalling envelope and then they are considered to be recently formed in the current existing molecular clouds. The catalog has unveiled the spatial distribution of thousands of YSOs, enabling us to carry out the direct comparison of the Star Formation Efficiency (SFE) with gas temperature and density.

We calculated the surface number density of YSOs, \(N_*\), by using the Spitzer catalog at the same grid as our CO dataset (Figure 3.20). We used both of the 'disked' and 'protostar' objects in their catalog. We then derived the distribution of
Figure 3.20: Map of the YSOs surface density (Megeath et al. 2012). Contours show the integrated intensity of the $^{12}$CO($J = 2–1$) smoothed to 10′ (HPBW) for reference. The contour levels are 2, 10, 20, 50, and 100 K km s$^{-1}$.
3.5. DISCUSSION

3.5.1 Relationship of the cloud physical properties and star forming activity

In this subsection, we discuss the relationship between the cloud properties and the star formation activities in the Orion molecular cloud. Figure 3.20 clearly shows that there are more YSOs in regions where the gas column density is higher. Figure 3.21a shows that the number of YSOs are positively correlated with the gas column density, although the tendency is unclear in the case of the Orion B2. This trend is also seen

![Figure 3.21: Plot of the average number of YSOs versus (a) the column density and (b) the volume density. Triangles, squares, plus signs, and crosses denotes the regions A1, A2, B1, and B2, respectively.](image)

the SFE by the following equation,

$$\text{SFE} = \frac{M_*}{M_* + M_{\text{cloud}}}; \quad (3.15)$$

where $M_*$ is the mass of YSOs estimated as $M_* = m_* N_*$ assuming the mean stellar mass $m_* = 0.5M_\odot$ (Evans et al. 2009), and $M_{\text{cloud}}$ is the mass of the molecular gas. We use the LTE mass derived from $^{13}\text{CO}(J = 1-0)$ line emission for the total molecular gas mass. We calculated the averaged SFEs for each subregions introduced in §3.4.1. Results are summarized in Table 3.5. The subregions in the Orion A have higher SFE than those of the Orion B subregions.
Figure 3.22: Plot of the average SFE versus (a) the column density and (b) the volume density. Symbols are same as Figure 3.21. The solid lines indicate the relationships of SFE = 0.06α⁻¹n¹/² for α = 70, 90, 120, and 200, respectively.

in the gas density as shown in Figure 3.21b, indicating that the density of the gas is a key for the activity of the star formation therein. Table 3.5 summarizes the SFEs of the subregions. It is very striking that the SFE of the Orion A2 subregion is much higher compared with the other subregions. However the average column density, temperature, and density of the Orion A2 are not significantly different from the other subregions, implying that the SFE is not necessarily determined by the overall properties of the molecular clouds. Figure 3.22a shows the relation of SFE with the gas column density, and Figure 3.22b with the gas volume density. It is obvious that the SFE is well correlated with the gas density, i.e., more stars are formed in denser regions. The poorer correlation in Orion B1 may be a result of the gas dispersion due to the active star formation in NGC2024 and the external disturbances as discussed in the next subsection.

The positive correlation between the gas number density and the SFE indicates that the time scale from gas to protostar, $T_{\text{collapse}}$, is shorter for denser gas if we assume a steady star formation. In this case, the total mass of the formed stars $M_*$ is proportional to the total gas mass $M_{\text{cloud}}$ and inversely proportional to the time scale of star formation $T_{\text{collapse}}$ (i.e., $M_* \propto M_{\text{cloud}} / T_{\text{collapse}}$). Therefore, the SFE is inversely proportional to $T_{\text{collapse}}$. If $T_{\text{collapse}}$ is described as $\alpha T_{\text{ff}}$, where $T_{\text{ff}}$ is the free fall time scale, the SFE is proportional to $(\alpha T_{\text{ff}})^{-1}$, and then to $\alpha^{-1}n^{1/2}$, where $n$ is the volume density of the gas. The $\alpha$ depends on the balance among the self-gravity and the other forces, unity for self-gravity dominating case, and then $T_{\text{collapse}}$ may depend on the
volume density. The data in Figure 3.22b shows that the SFE is roughly explained as 
SFE \propto n^{1/2}, although the scatter is large, and the scatter suppose that the dynamics 
of the gas is different from region to region.

The gas temperature is the highest toward the region around the Orion KL, probably due to the heating by massive stars forming therein. There is a slight temperature 
enhancement along the ridge of Orion A, and this may be due to the star formation 
inside. We see the enhancement of gas temperature toward NGC2023 in Orion B, 
although the gas temperature seems not to be well correlated with the star formation 
activities in the Orion B.

It is to be noted that the Spitzer catalog of Megeath et al. (2012) has not covered 
the whole extent of the molecular gas. A recent study with Akari and WISE catalogues 
indicates that there are YSOs identified outside the Spitzer area (Tóth et al. 2013). 
We are also interested in the star formation efficiency in somewhat isolated clumps like 
the EC clumps and the Northern clumps, and this is one of subjects in a subsequent 
paper.

### 3.5.2 Effect of the surrounding environment

In this subsection, we discuss the effect of the surrounding environment on the physical 
properties of the molecular clouds. Figure 3.23 shows the intensity distribution of Hα 
compared with the molecular gas distribution. There are some intense peaks which 
corresponding to Orion KL, the southern side of the Orion B cloud, and the Bernard 
loop. The Bernard loop is considered to have formed by the interaction with an old 
supernovae, and the other H_\text{II} regions are considered to have formed by the Ori OB1 
association. The Bernard loop seems to have no interaction with the molecular cloud 
as suggested by Sakamoto et al. (1994).

The Hα peak toward the Orion KL is clearly due to the current active massive 
star formation therein. The Hα enhancement toward the southern side of the Orion 
B consists of two parts; one is NGC2024 and the other is along the southern edge of 
the Orion B cloud. The former seems to reflect the ongoing star formation activities. 
The latter is ionized by the strong UV radiation from the OB1b subgroups. There 
is a clear gas density and temperature enhancement toward the southern edge of 
the Orion B1 as shown in Figures 3.19 and 3.18, and this fact suggests that the 
strong stellar wind and UV radiation compress and heat the molecular gas. Another 
important feature of the Orion B1 is that the gas temperature is higher than other 
subgroups as a whole. Especially, the temperature is higher toward the surrounding 
edge of the Orion B1. This implies that the Orion B1 cloud is surrounded by the H_\text{II}
Figure 3.23: Distribution of the Hα intensity (Gaustad et al. 2001) superposed on the contour of integrated intensity of the $^{12}$CO($J = 2–1$) which smoothed to 10′(HPBW) resolution for reference. The contour levels are 2, 10, 20, 50, and 100 K km s$^{-1}$. 
region, heating the outer edge of the molecular gas of the Orion B.

3.6 Summary

We have observed the $J = 2–1$ lines of $^{12}$CO, $^{13}$CO, and C$^{18}$O toward almost the entire extent of the Orion A and B molecular clouds. By comparing with $J = 1–0$ data of $^{12}$CO, $^{13}$CO, and C$^{18}$O observed with the Nagoya 4-m telescopes, we derived the spatial distribution of the physical properties of the molecular clouds and discussed the relation between the cloud physical properties and its surrounding conditions and star formation in the clouds. The main results are summarized as follows.

1. The spatial distributions of each $J = 2–1$ emission globally resembles that of the corresponding $J = 1–0$ emission although we observe some differences which reflects the difference in the physical properties. The general trend is that the distribution of each $J= 2–1$ emission is similar to that of the corresponding $J = 1–0$ emission toward the region with the high-intensity, although each $J = 1–0$ line is more widely distributed than that of the corresponding $J = 2–1$ line toward the region of low-intensity.

2. The complicated velocity structures are evident in the Orion molecular cloud complex. Various features are identified in spatial and velocity distributions of these lines. The Orion A cloud (L1641) includes the main ridge (containing OMC2/3, Orion KL, L1641N, L1641S, and NGC1999), northern clumps, and extended components/clumps. The Orion B cloud (L1630) includes northern cloud (containing NGC2068, NGC2067), southern cloud(NGC2023, NGC2024), and the 2nd component.

3. The $^{12}$CO($J = 2–1$)/$^{12}$CO($J = 1–0$) intensity ratio ($R_{21}^{21}/R_{11}^{11}$) is greater than unity in the regions close to the H$_{II}$ region or the cloud boundary facing to the OB association. This high ratio can be explained if the $^{12}$CO lines are optically thin, and the emitted region is dense to excite to the $J = 2$ level and is also warm. This fact suggests the interaction of the radiation or stellar winds from the massive stars.

4. We derived the gas mass from the observed line intensities. We used X-factor of $1.8 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s (Dame et al. 2001) for optically thick lines of $^{12}$CO($J = 1–0$) and assumed the LTE condition for the optically thin lines of
\(^{13}\text{CO}(J=1-0), \ ^{13}\text{CO}(J = 2-1), \ C^{18}\text{O}(J = 1-0), \text{ and } C^{18}\text{O}(J = 2-1)\). The X-factor masses are similar to that derived from \(^{13}\text{CO}(J = 1-0)\) intensity. The mass derived from \(J = 2-1\) is lower than that from \(J = 1-0\) by a factor of about 3. This indicates that the \(J = 2-1\) optically thin lines are sub-thermally excited, and trace denser gas than \(J = 1-0\) lines.

5. The spatial distributions of the gas density, \(n(\text{H}_2)\), and the gas temperature, \(T_{\text{kin}}\), were derived with the LVG analyses under the assumptions of the uniform fractional abundance of the CO and the constant \(dr/dv\). The gas temperature is higher in the area around the H\(_\text{II}\) region with > 100 K. The gas density is higher (\(n(\text{H}_2) > 2000 \text{ cm}^{-3}\)) in the cloud edge facing to the H\(_\text{II}\) region. These facts suggest the strong stellar wind and UV radiation from the surrounding massive stars are compressing the molecular gas.

6. The YSOs surface number density and the SFE are well positively correlated with the gas density. This fact indicates that the star formation is more effectively taking place in the denser environment.
Chapter 4

Summary

4.1 Summary of This Thesis

The 1.85-m millimeter/sub-millimeter wave telescope was developed in order to reveal the distribution of the physical properties of the molecular clouds and to compare it with the star formation activities. The telescope has the following features:

1. The main dish and the optics are created so as to achieve molecular line observations at 115, 230, and 345 GHz. The surface accuracy of the main dish is measured to be 19 µm rms. The current target frequency is 230 GHz band, and the 2.7 beam size (FWHM) of the telescope is suitable to obtain a large scale distribution of molecular gas which also can be compared with large-scale observation data in various wavelengths.

2. The development of a waveguide-type 2SB SIS receiver enables us to observe molecular clouds in the \( J=2-1 \) rotational lines of carbon monoxide and the isotopes (\(^{12}\)CO, \(^{13}\)CO, C\(^{18}\)O) simultaneously. The simultaneous observations provide us the multi-line dataset with the similar qualities and accurate pointing that are suitable for the analyses of line ratios.

3. Automatic operations are realized owing to a unified system we developed on python. The system brings us a high observation efficiency with minimum machine dead-time as well as the minimized burden for the operators who conduct around-the-clock monitoring during the observation season. The flexibility enables us to port the system to the other telescope systems (e.g., SPART, NANTEN2).
4. The telescope is installed at the Nobeyama Radio Observatory, and the commissioning of the telescope confirmed the following performances. The beam size (HPBW) was measured to be 2.7\', and the typical system noise temperatures including the atmosphere are from 200 to 400 K. The pointing accuracy is observed to be better than 30\'' (peak-to-peak). Implementation of the OTF mapping was successful, and the typical observation efficiency, a ratio of total ON time over the total observation time, is calculated to be about 60%.

Using the newly-developed 1.85-m telescope, we carried out the multi-line CO ($J=2–1$ of $^{12}\text{CO}$, $^{13}\text{CO}$, $^{18}\text{CO}$) survey toward the Orion giant molecular clouds. The conclusions of the observations are follows:

1. The spatial distribution of each $J=2–1$ emission globally resembles that of the corresponding $J=1–0$ emission although we observe some differences which reflects the difference in the physical properties. The general trend is that the distribution of each $J=2–1$ emission is similar to that of the corresponding $J=1–0$ emission toward the region with the high-intensity, although each $J=1–0$ line is more widely distributed than that of the corresponding $J=2–1$ line toward the region of low-intensity.

2. The small scale structures are found in the Extended Components owing to the high angular resolution and large observational area that are enabled by the telescope.

3. The $^{12}\text{CO}(J=2–1)/^{12}\text{CO}(J=1–0)$ intensity ratio ($R_{21}^{21}/R_{10}^{10}$) is greater than unity in the regions close to the H$_{\text{II}}$ region or the cloud boundary facing to the OB association. This high ratio can be explained if the $^{12}\text{CO}$ lines are optically thin, and the emitted region is enough dense to excite to the $J=2$ level and is also warm. This fact suggests the interaction of the radiation or stellar winds from the massive stars.

4. From the comparisons of the different assumptions to derive the gas mass, we conclude that the $J=2–1$ optically thin lines are mostly sub-thermally excited, and trace denser gas than $J=1–0$ lines.

5. The spatial distributions of the gas density, $n(\text{H}_2)$, and the gas temperature, $T_{\text{kin}}$, were derived with the LVG analyses under the assumptions of the uniform fractional abundance of the CO and the constant $dr/dv$. The gas temperature is higher in the area around the H$_{\text{II}}$ region with $> 100$ K. The gas density is
higher \( n(\text{H}_2) > 2000 \text{ cm}^{-3} \) in the cloud edge facing to the \( \text{H}_\text{II} \) region. These facts suggest the strong stellar wind and UV radiation from the surrounding massive stars are compressing the molecular gas.

6. The YSOs surface number density and the SFE are well positively correlated with the gas density. This fact indicates that the star formation is more effectively taking place in the denser environment.

### 4.2 Future Prospects

This thesis presents the results of the large-scale observations of the physical properties of the molecular clouds in multiple molecular lines, and then it is found that the combination of the optically thick line and different transitions of the optically thin lines are important to derive the cloud properties. Large-scale observations of the \( J=2–1 \) transition of CO lines are however anything more than just started. Hence, there are lots of challenges to be addressed. Here we point out some directions for the future studies.

The first is a study of the other molecular clouds. In this thesis, we carried out the study of the giant molecular clouds associated with \( \text{H}_\text{II} \) regions and revealed the spatial distribution of the temperature and density. Similar studies toward the dark clouds (e.g., Taurus, Polaris Flare) and the other GMCs (e.g., Cygnus, California) would provide vital information to understand the relation between the cloud properties and the surrounding environment. These fundamental datasets of the GMC properties are necessary for the comparisons with the surveys in other wavelengths of the Galactic GMCs (e.g., taken with \textit{Spitzer} and \textit{Herschel}) and the surveys of the GMCs in the external galaxies taken with ALMA.

The second is a study of the \( \text{C}^{18}\text{O}(J=2–1) \). In this thesis, we used \( ^{12}\text{CO} \) and \( ^{13}\text{CO} \) of \( J=1–0 \) and \( J=2–1 \) for the analyses, and the cloud properties are derived toward the region where density is about \( 10^3 \text{ cm}^{-3} \). By using the combination of the \( \text{C}^{18}\text{O} \) and \( ^{13}\text{CO} \), it is expected that the properties of the higher density region about \( 10^4 \text{ cm}^{-3} \) are derived. These analyses will enable us to investigate the hierarchical structure of the density which exists in the molecular clouds.

The third is an application to the lines of the other molecules. We confirmed the usefulness of the analyses for the combination of the CO lines. The similar analyses for the combination of the higher density tracers such as CS and \( \text{HCO}^+ \) by observing with the better angular resolution (e.g., using Nobeyama 45-m, ALMA), would
provide us wealth of information of the density structure in the inner dense region. For example, the combination of the $^{32}$S($J$=2–1), $^{34}$S($J$=1–0), and $^{34}$S($J$=2–1) lines is possibly worthy for the analyses. These observations would provide us the significant perceptions for the whole picture of the evolution of molecular clouds.
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