Mid-J CO Line Observations of Protostellar Outflows in the Orion Molecular Clouds

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Abstract

Ten protostellar outflows in the Orion molecular clouds were mapped in the 12CO/13CO J = 6 → 5 and 12CO J = 7 → 6 lines. The maps of these mid-J CO lines have an angular resolution of about 10′′ and a typical field size of about 100″. The physical parameters of the molecular outflows were derived, including mass transfer rates, kinetic luminosities, and outflow forces. The outflow sample was expanded by reanalyzing archival data of nearby low-luminosity protostars to cover a wide range of bolometric luminosities. Outflow parameters derived from other transitions of CO were compared. The mid-J (Jup ≈ 6) and low-J (Jup ≤ 3) CO line wings trace essentially the same outflow component. By contrast, the high-J (up to Jup ≈ 50) line emission luminosity of CO shows little correlation with the kinetic luminosity from the J = 6 → 5 line, which suggests that they trace distinct components. The low-/mid-J CO line wings trace long-term outflow behaviors, while the high-J CO lines are sensitive to short-term activities. The correlations between the outflow parameters and protostellar properties are presented, which shows that the strengths of molecular outflows increase with bolometric luminosity and envelope mass.

Unified Astronomy Thesaurus concepts: Protostars (1302); Star formation (1569); CO line emission (262); Stellar jets (1607); Radio astronomy (1338)

1. Introduction

Stars are formed in dense molecular clouds, and the feedback from protostars in the form of radiation and outflows is thought to play an important role in mediating the collapse of cloud cores and the accretion of material onto the protostars (Krumholz et al. 2014; Offner et al. 2014; Osorio et al. 2017). Therefore, detailed studies of protostellar feedback are required for understanding the physical processes that control the ultimate masses of newly forming stars. The rotational transitions of CO provide a unique window into protostellar feedback. In the last few decades, many outflows were studied with low-J CO lines (Jup ≤ 3) tracing cold entrained gas (Bontemps et al. 1996; Arce & Sargent 2006; Dunham et al. 2014). Relatively warm (≥30 K) gas components were studied with mid-J CO lines (Jup ≈ 6; van Kempen et al. 2009, 2016; Yildiz et al. 2012, 2015).

High-J CO lines (up to Jup ≈ 50) in the far-IR range were observed with instruments such as the Photodetecting Array Camera and Spectrometer (PACS) on board the Herschel Space Observatory (van Kempen et al. 2010; Herczeg et al. 2012; Visser et al. 2012; Manoj et al. 2013, 2016). The rotational diagrams of far-IR CO lines from protostars can be fit with temperatures ranging from 200 to 1000 K assuming local thermodynamic equilibrium (van Kempen et al. 2010) or higher than 2000 K assuming an isothermal, subthermally excited gas component (Manoj et al. 2013). The origin of this hot gas is being debated. The outflow pushes out the surrounding molecular gas, and the outflow cavity inflates. Visser et al. (2012) argued that the hot gas is heated by a mixture of ultraviolet heating and C-type shocks, while Manoj et al. (2013) argued that the CO lines originate in shock-heated, hot (>2000 K), subthermally excited molecular gas. Therefore, it is important to investigate the relative contributions of heating by ultraviolet radiation and shocks. In the case of shocks, it is needed to understand whether the shocks are located at the cavity walls or within the outflow itself.

The Herschel Orion Protostar Survey (HOPS) is a Herschel open-time key program designed to study protostellar evolution using a combination of Herschel/PACS imaging and spectroscopy (Fischer et al. 2010; Furlan et al. 2016). Using the HOPS data, Manoj et al. (2013) presented the far-IR CO emission from 21 protostars in the Orion molecular clouds (OMCs) at a distance of ∼420 pc (Menten et al. 2007; Kim et al. 2008). Manoj et al. (2013) found that the total luminosity of the CO lines in the range from J = 14 → 13 to 46 → 45 exhibited a strong correlation with the protostellar bolometric luminosity (Lbol) but not with the bolometric temperature (Tbol) or the envelope density estimated from model fits to the spectral energy distributions (SEDs). Manoj et al. (2013) argued that the dominant component of the far-IR CO emission is not caused by ultraviolet heating. In addition, they found that the rotational temperatures (which vary with J) were remarkably independent of protostellar luminosity, envelope density, or bolometric temperature. They argued that the invariant rotational temperatures can be explained by a gas component with high temperature (>2000 K) and moderate density (n(H2) < 104 cm−3). In this regime, the rotational curve shows a weak dependence on the gas kinetic temperature (also see Neufeld 2012). They proposed that the emission arises from the shock-heated gas in the protostellar wind that fills the outflow cavity.
Table 1

| Transition     | Frequency (GHz) | Beam (arcsec) | $T_{mb}^a$ (K) |
|---------------|----------------|--------------|---------------|
| $^{13}$CO $J = 6 \rightarrow 5$ | 661.067280 | 9.4          | 1100          |
| $^{12}$CO $J = 6 \rightarrow 5$ | 691.473076 | 9.0          | 1700          |
| $^{12}$CO $J = 7 \rightarrow 6$ | 806.651806 | 7.7          | 4000          |

Note. $^a$ Mean system temperature.

In this paper, we present the results of a survey of protostellar outflows observed in the $^{12}$CO/$^{13}$CO $J = 6 \rightarrow 5$ and $^{12}$CO $J = 7 \rightarrow 6$ lines. The outline of the paper is as follows. Section 2 explains the observations. The survey results and the physical parameters of the CO outflows are given in Section 3. The protostellar outflow activities are discussed in Section 4. The observed sources are described in detail in Section 5. A summary is given in Section 6. This paper focuses on the presentation of the data, and further analyses of the results will be presented in the future.

2. Observations and Data

2.1. Observations

Outflow activities of the protostars in the far-IR CO study by Manoj et al. (2013) were examined, and 10 outflows driven by relatively luminous protostars were selected. (See Section 2 of Manoj et al. 2013 for the explanation of how the far-IR targets were selected.) A total of nine regions were observed, because one of the regions contains two target outflows. The CHAMP$^+$ instrument on the APEX 12 m telescope in Chile was used to observe the $^{13}$CO/$^{12}$CO $J = 6 \rightarrow 5$ and $^{12}$CO $J = 7 \rightarrow 6$ lines. Most maps were obtained on 2012 August 28 and 29, and two maps of the $^{13}$CO $J = 6 \rightarrow 5$ line were made on 2014 November 6. The CHAMP$^+$ instrument consists of two heterodyne receiver arrays, each with 7 pixel detector elements and a usable intermediate-frequency bandwidth of 2 GHz pixel$^{-1}$, for simultaneous operations in the 620–720 and 780–950 GHz frequency ranges (Kasemann et al. 2006; Güsten et al. 2008). Simultaneous observations were carried out in the lower- and higher-frequency bands with the settings of $^{13}$CO $J = 6 \rightarrow 5$ and $J = 7 \rightarrow 6$, respectively. The observations were carried out under good weather conditions (precipitable water vapor $\approx 0.5$ mm). The telescope pointing and focus checks were typically made at 1 hr intervals on various planets and other strong sources. The pointing was found to be accurate within 2". Table 1 lists the parameters of the observed lines.

The target protostars are listed in Table 2. For most of the target regions, except for HOPS 370, each of the $^{12}$CO maps covered a 110" $\times$ 110" area with the on-the-fly observing mode. The HOPS 370 maps cover a larger area to include the HOPS 368 outflow. For each mapping field, the background subtraction was done by observing a reference position at an offset of 10′ in the R.A. Because the maps have elevated noise levels near the edge, the outer areas were excluded by masking. For each of the $^{12}$CO $J = 6 \rightarrow 5$ maps, the area with a noise level larger by a factor of 7 than that of the central area was masked out. The effective size of the map is $\sim 90''$ in diameter (about 100$''$ $\times$ 170$''$ for the HOPS 370 region). For the $^{13}$CO $J = 6 \rightarrow 5$ and $^{12}$CO $J = 7 \rightarrow 6$ maps, the masking threshold was a factor of 3, and the effective map size is somewhat smaller.

The spectra were converted to the main beam temperature scale with a forward efficiency of 0.95, and the beam efficiencies taken from the CHAMP$^+$ website. The original velocity resolution of the spectra is about 0.3 km s$^{-1}$. The spectra were smoothed to a velocity resolution of 1 km s$^{-1}$. All of the maps were convolved to a resulting angular resolution of 10″. The mean noise levels (1σ for a channel width of 1 km s$^{-1}$) at the target protostellar positions are about 0.24, 0.23, and 0.30 K for the $^{13}$CO $J = 6 \rightarrow 5$, $^{12}$CO $J = 6 \rightarrow 5$, and $^{12}$CO $J = 7 \rightarrow 6$ lines, respectively. The data were processed with the GILDAS/CLASS software from Institut de Radioastronomie Millimétrique.

2.2. Archival Data of Nearby Protostars

A survey of outflows driven by relatively low-mass protostars in nearby molecular clouds was presented by Yildiz et al. (2015). These data will be incorporated into the statistical analysis in Section 4. Instead of using the values given by Yildiz et al. (2015), however, we will use the outflow parameters recalculated with the method described in Section 3. There are two reasons for reprocessing the raw data. First, there are some inconsistencies between the observed data and the derived values in Yildiz et al. (2015). For example, the mass outflow rate, force, and luminosity of the red lobes in Tables 2 and 3 of Yildiz et al. (2015) are almost always larger than those of the corresponding blue lobes, even though the maps and spectra do not show such trends. Second, some parameters, such as maximum velocities, were taken from the $J = 3 \rightarrow 2$ line data, which tend to produce larger values of outflow parameters than those derived using the $J = 6 \rightarrow 5$ line data only.

Details for calculating the new outflow parameters are given in Appendix A. In the discussions below, the outflow parameters of low-mass protostars refer to the values presented in Appendix A.

3. Results

3.1. Overview

Ten outflows were identified from the nine regions observed, with the HOPS 370 map containing the HOPS 370 and HOPS 368 outflows. Most of the outflows show clear blue–red bipolar outflow structures, which is consistent with previous studies with low-J CO lines (Aslo et al. 2000; Stanke et al. 2002; Shimajiri et al. 2008; Takahashi et al. 2008; Takahashi & Ho 2012). Table 2 lists the properties of the protostars driving these outflows (Furlan et al. 2016).

Figure 1 presents large-scale infrared images composed with the Wide-field Infrared Survey Explorer (WISE) data. The WISE 4.6 μm emission images are useful for studying protostellar jets, similar to the Spitzer IRAC 4.5 μm images showing shock-excited line features (De Buizer & Vacca 2010). The outflow features are seen clearly in the WISE three-color composite image as green features. In particular, the WISE images show that the HOPS 310 and HOPS 288 outflows are extended over a length of $\sim 30''$.

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Kang et al.

[8] https://www.mpifr-bonn.mpg.de/~4480868/efficiencies

[9] http://www.iram.fr/IRAMFR/GILDAS
The Astrophysical Journal Supplement Series, 255:2 (25pp), 2021 July

Kang et al.

Table 2
Target Protostars

| HOPS  | R.A. (J2000.0) | Decl. (J2000.0) | \(L_{\text{bol}}\) (\(L_\odot\)) | \(T_{\text{bol}}\) (K) | \(M_{\text{env}}\)* (\(M_\odot\)) | \(I\) | Association* |
|-------|----------------|----------------|--------------------------|----------------|-------------------------------|------|----------------|
| 310   | 05 42 27.67    | −01 20 01.0    | 13.8                     | 51.8           | 6.3                           | 70   | L1630 HH 92 IRAS 05399−0121 |
| 88    | 05 35 22.44    | −05 01 14.2    | 15.8                     | 42.4           | 6.8                           | 70   | OMC 3 MMS 5                  |
| 68    | 05 35 24.31    | −05 08 30.5    | 5.7                      | 100.6          | 7.5                           | 50   | OMC 2 FIR 2                  |
| 370   | 05 35 27.62    | −05 09 33.5    | 360.9                    | 71.5           | 15.6                          | 87   | OMC 2 FIR 3, VLA 11          |
| 368d  | 05 35 24.72    | −05 10 30.4    | 68.9                     | 137.5          | \(\ldots\)                    | 18   | OMC 2 VLA 13                 |
| 60    | 05 35 23.33    | −05 12 03.2    | 21.9                     | 54.1           | 5.6                           | 81   | OMC 2 FIR 6b, CSO 25         |
| 56    | 05 35 19.46    | −05 15 32.8    | 23.3                     | 48.1           | 3.5                           | 50   | OMC 2 CSO 33                 |
| 182   | 05 36 18.84    | −06 22 10.2    | 71.1                     | 51.9           | 27.5                          | 76   | L1641N MM1                   |
| 203   | 05 36 22.85    | −06 46 06.2    | 20.4                     | 43.7           | 10.8                          | 70   | L1641 HH 1/2 VLA 1           |
| 288   | 05 39 55.94    | −07 30 28.1    | 135.5                    | 48.6           | 52.1                          | 76   | L1641 S3 MMS 1               |

Notes. The HOPS source number and protostellar parameters are from Furlan et al. (2016). Units of R.A. are hours, minutes, and seconds, and units of decl. are degrees, arcminutes, and arcseconds.

* Envelope mass calculated from 850 \(\mu\)m flux densities. See Section 4.3 for details.

* Inclination to the line of sight in degrees from Furlan et al. (2016).

* Association from Mezger et al. (1990), Rodriguez et al. (1990), Chini et al. (1997), Lis et al. (1998), Reipurth et al. (1999), Stanke et al. (2000), and Stanke & Williams (2007).

* HOPS 368 is located in the southwestern corner of the HOPS 370 field.

Figures 2 and B1–B9 show the spectra and maps of the target outflows. In each figure, the top panels show representative spectra. The middle panels show the line intensity maps, integrated over the whole velocity range. The bottom panels show the maps of molecular outflows.

The \(^{12}\text{CO}\) \(J = 6 \to 5\) and \(J = 7 \to 6\) line profiles at the protostellar positions show comparable emission strengths between the line wings indicating strong outflow activities and the line cores arising from the protostellar envelopes. The typical wing-to-core ratios of the integrated intensities are 0.8 and 0.7 for the \(^{12}\text{CO}\) \(J = 6 \to 5\) and \(J = 7 \to 6\) lines, respectively. The wing-to-core ratios can be much larger at outflow peak positions away from the protostellar positions. Table 3 lists the Gaussian-fit parameters of the \(^{13}\text{CO}\) \(J = 6 \to 5\) spectra at the protostellar positions. The \(^{13}\text{CO}\) line width ranges from 1.7 to 3.1 km s\(^{-1}\). Some \(^{12}\text{CO}\) spectra show self-absorption features, but the \(^{13}\text{CO}\) spectra do not, suggesting that the \(^{13}\text{CO}\) line is mostly optically thin.

The velocity limits of the \(^{12}\text{CO}\) line wings were determined carefully for each outflow. The inner limit (\(V_{\text{in}}\)) was determined from the FWHM of the averaged quiescent emission, which was extracted from the spatial region not associated with the outflow, i.e., several pixels in the region outside the first contours in the outflow maps of Figures 2 and B1–B9. This process needed a few iterations. The outer velocity limit (\(V_{\text{out}}\)) is at the velocity where the wing intensity reaches the \(1\sigma\) level for the first time, at the position where the wing is the widest, except for HOPS 68 and 88. For these two outflows, the outer limits are set to values high enough to include the emission from the extremely high velocity bullets that were reported in previous studies (Gómez-Ruiz et al. 2019; Matsushita et al. 2019). Table 4 lists the velocity limits for the blue and red line wings, and they are also marked on the spectra in panels (b) and (c) of Figures 2 and B1–B9.

Integrated intensity maps of the three lines are presented in the middle panels of Figures 2 and B1–B9. The line-wing maps of the \(^{12}\text{CO}\) lines are presented in the bottom panels. The contour maps show the line intensity integrated over the velocity range listed in Table 4, and the contour levels are given in Table 5. The lowest contour levels were chosen to delineate the outflows as clearly as possible, low enough to include the outflows and high enough to exclude the ambient clouds.

3.2. Outflow Properties

Several quantities were measured for each outflow lobe to describe the outflow properties. The length of the outflow lobe, \(R_{\text{lobe}}\), is the extent of the outflow in the line-wing map from the protostellar position. Some of the outflows are extended beyond the mapping fields, and the corresponding \(R_{\text{lobe}}\) is the distance to the edge of the map. For these outflows, the physical quantities described below are relevant to the mapped portion of the outflow, not the whole outflow. The maximum outflow velocity, \(V_{\text{max}}\), is the maximum velocity of the line wing relative to the centroid velocity, \(V_{\text{out}}−V_{\text{c}}\), as listed in Table 4. The dynamical time is calculated by

\[ t_{\text{dyn}} = \frac{R_{\text{lobe}}}{V_{\text{max}}} . \] (1)

The mass of the molecular outflow is calculated by

\[ M_{\text{CO}} = \mu_{H_2} M_{H_2} A \sum_{l} N_{H_2,l} \] (2)

where \(\mu_{H_2}\) is the mass of the hydrogen atom, \(\mu_{H_2}\) is the mean molecular weight per hydrogen molecule (\(\mu_{H_2} = 2.8\); Kauffmann et al. 2008), \(A\) is the surface area of 1 pixel (2.75 × 2.75), \(N_{H_2,l}\) is the pixel-averaged \(H_2\) column density over the selected velocity range, and the sum is over spatial pixels encompassing the outflow seen in the contour maps.

Assuming that the emission from the outflow is optically thin (see below), the column density is proportional to the integrated intensity. For the outflow lobes showing predominantly blueshifted or redshifted emission, the integration was done over the velocity interval of \((V_{\text{out}}, V_{\text{in,b}})\) or \((V_{\text{in,r}}, V_{\text{out}})\), respectively. For the outflow lobes showing both blueshifted and redshifted emission, the integration was done over the velocity intervals of \((V_{\text{out}}, V_{\text{in,b}})\) and \((V_{\text{in,r}}, V_{\text{out}})\).

The column density \(N_{H_2}\) was obtained by adopting a typical abundance ratio of \([^{12}\text{CO}]/[H_2] = 10^{-4}\) (Ferking et al. 1982).
Figure 1. Color images composed of the WISE 12 (red), 4.6 (green), and 3.4 (blue) μm images for (a) HOPS 310 with HH flows, (b) HOPS 182, (c) HOPS 203 with HH flows, and (d) HOPS 288. Yellow boxes show the areas covered in this work. Open circles mark HOPS protostars, and plus signs represent the driving sources of the target outflows. Crosses mark HH objects associated with the target outflows. White arrows indicate the large-scale outflows of HOPS 310 and HOPS 288. Panel (e) shows WISE color image for HOPS 88, 68, 370, 368, 60, and 56. The cyan region near the bottom of the map shows the area where the 12 μm emission is saturated.
An excitation temperature of $T_{\text{ex}} = 75$ K was assumed for consistency with other studies such as Yıldız et al. (2012, 2015). In principle, the excitation temperature can be estimated from the $^{12}\text{CO} \ J = 7 \rightarrow 6 / J = 6 \rightarrow 5$ line ratio. The excitation temperatures at the positions of the strongest $^{12}\text{CO} \ J = 6 \rightarrow 5$ wing emission were estimated using the integrated intensities.
The kinetic energy within each velocity channel in each lobe is calculated by summing over the same velocities and pixels as for the mass.

The mass outflow rate of each lobe is given by

$$M_{\text{CO}} = \frac{M_{\text{CO}}}{t_{\text{dyn}}}.$$  

\( E_{\text{v, pixel}} \) is the velocity of each channel with respect to the systemic velocity. The kinetic energy \( (E_{\text{CO}}) \) of each molecular outflow lobe is calculated by summing over the same velocities and pixels as for the mass.

The mass outflow rate of each lobe is given by

$$M_{\text{CO}} = \frac{M_{\text{CO}}}{t_{\text{dyn}}}.$$  

The molecular outflow kinetic luminosity and force of each lobe are computed by

$$L_{\text{CO}} = \frac{E_{\text{CO}}}{t_{\text{dyn}}}$$

and

$$F_{\text{CO}} = \sqrt{2M_{\text{CO}}L_{\text{CO}}}.$$  

respectively. Here CO as a subscript refers to the total mass, energy, and related quantities of molecular gas as traced by the CO emission.

In this study, the CO outflows are assumed to be optically thin. Previous studies in the \( J = 3 \rightarrow 2 \) line showed that outflows are optically thin at velocities larger than \( \sim 3 \) km s\(^{-1}\) away from the systemic velocity (van der Marel et al. 2013; Dunham et al. 2014). Considering the uncertainties of outflow parameters, the optical depth effect may be negligible (van der Marel et al. 2013). Therefore, the outflows are expected to be optically thin in the \( ^{12}\text{CO} \) \( J = 6 \rightarrow 5 \) line. In most cases of this survey, there is no detectable wing feature in the \( ^{12}\text{CO} \) line profiles. An exception is the blueshifted outflow of HOPS 288 (Figure B9(a)). It shows a winglike emission feature over a few velocity channels, and the \( ^{12}\text{CO} / ^{13}\text{CO} \) line ratio gives an optical depth of \( \sim 6 \) for the \( ^{12}\text{CO} \) \( J = 6 \rightarrow 5 \) line using a \( ^{12}\text{CO} / ^{13}\text{CO} \) abundance ratio of \( \sim 60 \) (Wilson & Rood 1994). This exceptional feature may be related to the fact that the envelope mass of HOPS 288 is very large (Table 2). It can be seen only at the protostellar position, and the correction factors for the mass and energy estimates of this lobe are 1.6 and 1.1, respectively. Therefore, the assumption of optically thin outflow is reasonable.
The line core usually contains a blend of emission from the ambient cloud and the outflow. The emission from the outflow in the velocity interval \(\left(V_{\text{in.b}}, V_{\text{in.r}}\right)\) is not included in the calculation of the integrated intensity. Previous studies suggested correction factors for this “missing” mass, ranging from \(\sim -2\) to \(\sim 40\), in the case of low-J CO line observations (see Section 4.3 of van der Marel et al. 2013 and Section 4.3 of Dunham et al. 2014). The mass estimate from the \(J = 6 \rightarrow 5\) line is less affected by this issue because the typical kinetic temperature of the ambient gas is much lower than the \(J = 6\) energy level (115 K above ground). Considering that the integrated intensities of the line wing and core are comparable (Section 3.1), the correction factor for mass would be smaller than \(\sim 2\). In regions near the protostars where the emission from the ambient cloud is strong, the innermost channels of line wings may contain a blend of emission from the outflow and the ambient gas. It is difficult to separate this “contaminating” ambient emission from the outflow emission. The effects of the missing and contaminating emission components may cancel out to a certain degree. This issue barely affects the estimates of kinetic energy because most of the contribution comes from high-velocity channels.

Corrections for the outflow inclination are necessary because the measured quantities are the velocity component along the line of sight and the outflow lobe size projected on the plane of the sky. In this paper, the inclination is defined to be the angle between the outflow axis and the line of sight (i.e., \(i = 0^\circ\) corresponds to a pole-on system). The inclination angles (listed in Table 2) were taken from Furlan et al. (2016) to treat the target sources consistently. Furlan et al. (2016) derived the best-fit inclination angles from the continuum SEDs of protostars. They used 30,400 different model SEDs to determine the best-fit model parameters for 330 young stellar objects (YSOs). There are 3040 models in a grid covering eight values for the total luminosity, four disk radii, 19 envelope infall rates that correspond to envelope densities, and five cavity opening angles. They used the envelope density profile of a rotating, collapsing cloud core with a constant infall rate (Terebey et al. 1984). Each model is calculated for 10 different inclination angles. The inclination angle can be degenerate with the envelope density and other parameters. (See the discussion in Sections 6.3 and 7.2 and Appendix B of Furlan et al. 2016.) Inclination corrections to the outflow length, dynamical time, energy, momentum, mass outflow rate, luminosity, and force have been applied in the way described by Dunham et al. (2014) and Plunkett et al. (2015).

The derived outflow parameters are listed in Table 6. The outflow parameters presented in this paper are corrected for the inclination. Corrections for the optical depth are applied to the blueshifted lobe of HOPS 288 only. No correction is applied for the missing or contaminating low-velocity emission components. The southwestern outflow lobe of HOPS 370 is omitted because this region is overly complicated (Section 5.4). Figure 3 shows a comparison of the outflow parameters derived from the two \(^{12}\text{CO}\) lines. The overall correlation is good, but the estimates from the \(J = 7 \rightarrow 6\) line tend to be smaller. This difference is mainly owing to the relatively low signal-to-noise ratios of the \(J = 7 \rightarrow 6\) data. For HOPS 288 and HOPS 310, the kinetic luminosities from the \(J = 7 \rightarrow 6\) line are much smaller than those from the \(J = 6 \rightarrow 5\) line, which is mainly owing to the differences in the maximum velocities measured with these lines. In the discussion below, the estimates from the \(J = 6 \rightarrow 5\) line are mainly used to discuss the outflow properties and star formation activities.

The outflow parameters of HOPS 370 are exceptionally large. Its molecular outflow luminosity is even larger than the bolometric luminosity, which is unusual. This anomaly is probably owing to the large inclination angle. The inclination correction factors (Dunham et al. 2014) are valid when all of the gas motion is parallel to the outflow axis, but the real outflow must have nonparallel velocity components. Because of the large inclination of the HOPS 370 outflow, its \(F_{\text{CO}}\) and \(L_{\text{CO}}\) are probably overestimated. Therefore, in the discussion below, HOPS 370 is excluded from the statistical analysis of outflow parameters.

It is difficult to estimate the uncertainties in individual outflow parameters because major contributions come from certain assumptions made in the calculations. By trying some reasonable alternative values, it seems that the largest contribution to the uncertainties comes from the inclination angle. Furlan et al. (2016) used a grid of inclination angles, equally spaced in \(\cos i\). The grid size may be considered as an estimate of the uncertainty. Scaling the grid size with the correction factors, the uncertainties in \(\log M_{\text{CO}}, \log F_{\text{CO}},\) and \(\log L_{\text{CO}}\) are \(\sim 0.08, \sim 0.15,\) and \(\sim 0.21\), respectively. These values may be optimistic because the inclination of the outflow cavity near the protostar is not necessarily exactly same as that of the large-scale outflow axis. Considering this issue and other sources of uncertainties, we will use uncertainties of 0.1 for \(\log M_{\text{CO}}, 0.2\) for \(\log F_{\text{CO}},\) and 0.3 for \(\log L_{\text{CO}}\). Note that our data will be combined with the data from other surveys for the statistical analysis. Therefore, these uncertainties are only nominal values as a rough guide to the interpretation of statistics.

4. Discussion

4.1. Comparison with Low-J CO Transitions

The mid-J CO lines \((J_{\text{up}} \approx 6)\) trace warm components of outflows, while the low-J lines \((J_{\text{up}} \leq 3)\) trace relatively cold components, as mentioned in Section 1. It is therefore interesting to compare the outflow parameters derived from these lines. Takahashi et al. (2008) observed some HOPS protostars in the OMC 2/3 region in the \(^{12}\text{CO}\) \(J = 3 \rightarrow 2\) line. Comparison of the spectra shows that the line wings are more pronounced, relative to the line core, in the \(J = 6 \rightarrow 5\) line than the \(J = 3 \rightarrow 2\) line.

The correlations between the outflow parameters derived from the two lines are shown in the top panels of Figure 4. When the outflow parameters of Takahashi et al. (2008) are used without modification, the correlations are moderately good, and the linear correlation coefficients (Pearson’s \(r\)) are \(r = 0.55, 0.64,\) and 0.68 for \(M_{\text{CO}}, F_{\text{CO}},\) and \(L_{\text{CO}},\) respectively. However, the ranges of the \(J = 3 \rightarrow 2\) parameters are narrower than those of the \(J = 6 \rightarrow 5\) parameters. This difference is mostly owing to the inclination angle. Takahashi et al. (2008) used either \(i = 45^\circ\) or \(70^\circ,\) depending on the outflow morphology. When the outflow parameters are corrected for the inclination angles used in this paper (Figure 4, bottom panels), the correlation becomes even stronger \((r = 0.81, 0.84,\) and 0.85), and the distributions of data points show that the outflow parameters from the two lines are nearly equivalent. These strong correlations suggest that the two lines trace essentially the same outflow component. The advantages in
observing outflows in the $J = 6 \rightarrow 5$ line over the $J = 3 \rightarrow 2$ line include higher angular resolution, higher contrast to the cold ambient gas, and smaller optical depth.

Though the outflow strengths from the two lines are similar, there are significant differences in the outflow timescales. The timescales of the CO outflows traced by the $J = 3 \rightarrow 2$ line in the study of Takahashi et al. (2008) are longer than those reported in this paper, typically by a factor of $\sim 5$. This contrast suggests that the molecular outflows may be steady over the range of timescales covered by the two studies (from $\sim 200$ to $\sim 30,000$ yr), which implies that the outflow kinetic energy is not easily converted to other forms of energy in these timescales. Eventually, over a longer timescale, molecular outflows may have disruptive effects on the dense cores, develop to parsec scales, feed the interstellar turbulence, and even disperse the parent clouds (Arce et al. 2007, 2010; Plunkett et al. 2013).

### 4.2. Comparison with High-J CO Transitions

The bolometric luminosity is a good proxy of the accretion luminosity at the current epoch. The high-J CO lines in the far-IR range trace hot gas components, and the far-IR CO luminosity ($L_{\text{CO}}^{\text{FIR}}$) is a good tracer of the shocked gas near the base of molecular outflows at the current epoch or in the recent past, within the last $\sim 100$ yr (Manoj et al. 2016). By contrast, the kinetic luminosities from single-dish observations in low- and mid-J CO lines trace the outflow power smoothed over a longer timescale, $300$–$20,000$ yr for the outflows studied in this paper. Therefore, it would be interesting to see how $L_{\text{CO}}^{\text{FIR}}$...
is related to the other two luminosities, $L_{\text{bol}}$, tracing short-term accretion activities, and $L_{\text{CO}}$, tracing long-term outflow activities.

The scatter diagrams of the three forms of luminosities are shown in Figure 5. The kinetic luminosity of the molecular outflow is defined by

$$ L_{\text{out}} = 2(L_{\text{CO}}^\text{blue} \cdot L_{\text{CO}}^\text{red})^{1/2}, $$

where $L_{\text{CO}}^\text{blue}$ and $L_{\text{CO}}^\text{red}$ are the kinetic luminosities from the $^{12}$CO $J = 6 \rightarrow 5$ and $J = 3 \rightarrow 2$ lines, respectively. The geometric mean is used because the fits to the outflow data in the next section are made in the logarithmic scale. The factor 2 is needed because $L_{\text{CO}}$ is the power per outflow lobe, while $L_{\text{out}}$ is the power per protostar. Note that $L_{\text{out}}$ is the kinetic luminosity of the molecular outflow, while $L_{\text{CO}}^\text{FIR}$ is the line-emission luminosity of the CO gas ($J_{\text{up}} = 14-46$).

Though both $L_{\text{out}}$ and $L_{\text{CO}}^\text{FIR}$ trace outflow activities, they show almost no correlation (Figure 5(c)), which suggests that the high-$J$ and low-/mid-$J$ lines trace very different components of molecular outflows. The reason may be that they have different timescales and their energetics are not directly related. While $L_{\text{out}}$ may depend on relatively global properties of protostellar envelopes, $L_{\text{CO}}^\text{FIR}$ may be sensitive to the local condition of shocked regions. Despite the different timescales, the bolometric luminosity shows a moderate correlation with $L_{\text{out}}$, because the accretion process is the underlying driving mechanism of outflows. The bolometric luminosity shows a relatively good correlation with $L_{\text{CO}}^\text{FIR}$, because they have
similar timescales and are directly related in energetics. (See Sections 4.1 and 5.3 of Manoj et al. 2016 for more discussions on these luminosities.) The comparisons presented above show that the low-/mid-J and high-J CO lines are complementary, and they can be useful in distinguishing the long-term (evolutionary) outflow behaviors from the short-term (episodic or variable) activities.

The results of a survey of protostars observed in the CO lines from \( J = 4 \rightarrow 3 \) to \( 13 \rightarrow 12 \) were presented by Yang et al. (2018). They found that multiple excitation mechanisms affect a wide range of CO energy levels with significant overlaps. They also found that the line-emission luminosity of the \( J = 6 \rightarrow 5 \) line shows a good correlation with the total CO luminosity. These findings suggest that resolving the CO emission structure both spectrally and spatially is critical to the understanding of the underlying physical processes.

4.3. Comparison with Protostellar Properties

The correlation between the outflow force and bolometric luminosity of protostars was revealed by Bontemps et al. (1996). Since then, many studies corroborated the \( L_{\text{bol}} - F_{\text{CO}} \) correlation (Hatchell et al. 2007; Curtis et al. 2010; van der Marel et al. 2013; van Kempen et al. 2016). Scatter diagrams between the outflow parameters and protostellar properties are shown in Figure 6. Such diagrams are often made by summing the quantities of the blueshifted and redshifted outflow lobes. The meaning of a simple sum, however, is unclear when the dynamic times of the two lobes are different. Therefore, the outflow parameters of each lobe are displayed separately in these figures. To cover a wide range of the parameter space, the data from this work (Tables 6 and A3) are combined with the \(^{12}\text{CO} \, J = 6 \rightarrow 5\) data of three intermediate-mass protostars (NGC 2071, Vela IRS 17, and IRAS 20050+2720) from van Kempen et al. (2016). Vela IRS 19 in the sample of van Kempen et al. (2016) is omitted because its \( T_{\text{bol}} \) is unknown. The protostellar parameters are from Furlan et al. (2016), Kristen et al. (2012), Froebrich (2005), and Strafella et al. (2015). (Some parameters are updated and listed in Appendix A.) As a whole, the sample covers a luminosity range of \( L_{\text{bol}} = 1.6 - 520 \, L_{\odot} \) and a temperature range of \( T_{\text{bol}} = 26 - 387 \, \text{K} \).

The scatter diagrams in the left panels of Figure 6 show clear trends of \( M_{\text{CO}}, F_{\text{CO}}, \) and \( L_{\text{CO}} \) increasing with \( L_{\text{bol}} \). The linear correlation coefficients are \( r = 0.68, 0.61, \) and 0.56, respectively. Performing a linear least-squares fit to each diagram, the best-fit lines are

\[
\log M_{\text{CO}} = (-6.91 \pm 0.03) + (0.98 \pm 0.02) \log L_{\text{bol}}, \\
\log F_{\text{CO}} = (-5.91 \pm 0.06) + (1.13 \pm 0.04) \log L_{\text{bol}}, \\
\log L_{\text{CO}} = (-2.99 \pm 0.09) + (1.28 \pm 0.06) \log L_{\text{bol}},
\]

where \( M_{\text{CO}} \) is in \( \dot{M}_{\odot} \, \text{yr}^{-1}, \) \( F_{\text{CO}} \) is in \( L_{\odot} \, \text{yr}^{-1} \, \text{km} \, \text{s}^{-1}, \) and \( L_{\text{CO}} \) and \( L_{\text{bol}} \) are in \( L_{\odot} \).

The slope of the \( L_{\text{bol}} - F_{\text{CO}} \) relation in this work is consistent with that given by van der Marel et al. (2013) but steeper than those of Bontemps et al. (1996) and Curtis et al. (2010). This difference probably comes from the coverage of \( L_{\text{bol}} \). The outflow sample of Bontemps et al. (1996) covers a range of \( L_{\text{bol}} = 0.2 - 41 \, L_{\odot}, \) and outflows were undetected for some protostars at the lower part of the range (see Figure 5 of Bontemps et al. 1996). Therefore, their \( F_{\text{CO}} \) data may be biased positively at the lower end of their \( L_{\text{bol}} \) range, and the slope may appear shallower.

The scatter diagrams between the outflow parameters and \( T_{\text{bol}} \) are shown in the central panels of Figure 6. They show trends of \( M_{\text{CO}}, F_{\text{CO}}, \) and \( L_{\text{CO}} \) decreasing with \( T_{\text{bol}} \). However, the linear correlation coefficients are small: \( r = -0.06, -0.12, \) and -0.16, respectively. The main reason is the large dispersions in the middle range of \( T_{\text{bol}} \) (40–100 K). Figure 6(a) of Curtis et al. (2010) shows a similar feature. This trend may be an evolutionary effect. At the low end of \( T_{\text{bol}}, \) the protostellar mass is small, the accretion luminosity is low, and, consequently, the outflow is relatively weak. The outflow becomes stronger as the protostellar mass increases. On the high side of \( T_{\text{bol}}, \) the envelope mass decreases with evolution, and the outflow gradually weakens. The evolution of outflow parameters with \( T_{\text{bol}} \) may be complicated and cannot be described with simple power-law fits. Despite the low degree of correlation, the \( T_{\text{bol}} - F_{\text{CO}} \) relation in this work is consistent with that given by Curtis et al. (2010; \( F_{\text{CO}} \propto T_{\text{bol}}^{-0.64}, \)) as shown by the dashed line in the middle panel of Figure 6, which suggests that the overall trend may be real. This complicated evolutionary trend shows that \( L_{\text{bol}} \) and \( T_{\text{bol}} \) should be considered together for proper analyses of outflow statistics.

In addition to \( L_{\text{bol}} \) and \( T_{\text{bol}}, \) it has been well known that the mass of the protostellar envelope shows a positive correlation with the outflow force (Bontemps et al. 1996; Curtis et al. 2010; van der Marel et al. 2013). However, the envelope mass derived from a continuum SED is highly model-dependent. For the outflow sample in this work, the masses derived by Kristen et al. (2012) are usually much larger than those of Furlan et al. (2016) for protostars with similar \( L_{\text{bol}} \) and \( T_{\text{bol}} \). This discrepancy may be caused by the differences in the model density profiles and the definitions of envelope mass, such as the inner and outer radii for integration.
For a simple comparison with other studies, the envelope masses ($M_{\text{env}}$) were derived from submillimeter flux densities using Equation (1) of Nutter & Ward-Thompson (2007). They assumed optically thin conditions, a dust temperature of 20 K, and a mass emissivity of 0.01 cm$^2$ g$^{-1}$ at a wavelength of 850 μm. The 850 μm flux densities were obtained from the catalogs in Nutter & Ward-Thompson (2007) and Di Francesco et al. (2008). Four objects in the outflow sample are not included in these catalogs. The flux density of HOPS 288 was obtained from van Kempen et al. (2012), and HOPS 368, Vela IRS 17, and BHR 71 are omitted.

The scatter diagrams in the right panels of Figure 6 show clear trends of $M_{\text{CO}}$, $F_{\text{CO}}$, and $L_{\text{CO}}$ increasing with $M_{\text{env}}$. The linear correlation coefficients are $r = 0.75$, 0.72, and 0.69, respectively. (These coefficients are essentially the same as those of $L_{\text{bol}}$ calculated with HOPS 368, Vela IRS 17, and BHR 71 excluded.) The best-fit lines are

$$\log M_{\text{CO}} = (-6.45 \pm 0.02) + (1.01 \pm 0.02)\log M_{\text{env}},$$  \hspace{1cm} (11)

$$\log F_{\text{CO}} = (-5.43 \pm 0.04) + (1.27 \pm 0.04)\log M_{\text{env}},$$  \hspace{1cm} (12)

$$\log L_{\text{CO}} = (-2.50 \pm 0.06) + (1.51 \pm 0.06)\log M_{\text{env}},$$  \hspace{1cm} (13)

where $M_{\text{env}}$ are in $M_\odot$.

The slope of the $M_{\text{env}}$–$F_{\text{CO}}$ relation in this work is steeper than those of Bontemps et al. (1996), Curtis et al. (2010), and van der Marel et al. (2013). This difference may be owing to the same reason mentioned above, in the discussion on the $L_{\text{bol}}$–$F_{\text{CO}}$ relation.

5. Individual Sources

5.1. HOPS 310

HOPS 310 is a Class 0 protostar associated with IRAS 05399–0121 in the LBS 30 core of the L1630 cloud (Furlan et al. 2016). It drives a giant Herbig–Haro (HH) flow (Bally et al. 2002). The infrared image (Figure 1(a)) shows several HH objects along the outflow.

The APEX CO maps (Figure 2) cover the $110' \times 110'$ region centered on HOPS 310. The blue CO outflow peak in the northwestern corner of Figures 2(g) and (h) corresponds to HH 92. At the position of HH 92, the $^{12}$CO spectra show
emission from the outflow only, with little emission from the ambient cloud.

5.2. HOPS 88/87

Several target outflows are located in the OMC 2/3 region (Figure 1(e)). The HOPS 88 mapping field was originally selected for both HOPS 87 and HOPS 88. Initial examination of the mapping data revealed that the HOPS 87 outflow is unsuitable for a detailed study, and it was subsequently removed from the target list.

HOPS 88 is a Class 0 protostar associated with OMC 3 MMS 5 (Chini et al. 1997; Furlan et al. 2016) and has the lowest $T_{\text{bol}}$ among the survey sample. It drives an outflow in the east–west direction (Williams et al. 2003; Takahashi et al. 2008). Several infrared knots were detected along the western flow (Yu et al. 1997; Takahashi et al. 2008).

In the central region of the CO mapping field, there are three protostars: HOPS 86, 87, and 88 (Figure B1). Only HOPS 88 shows a prominent CO outflow. This outflow shows clearly separated blue and red lobes. It has the largest $V_{\text{max}}$ among the survey sample, $\sim 100 \text{ km s}^{-1}$ for the blue wing and $\sim 70 \text{ km s}^{-1}$ for the red wing. HOPS 88 also shows the narrowest $^{13}\text{CO}$ $J = 6 \rightarrow 5$ line profile among the survey sample. The blue outflow lobe is much stronger than the red one. In the red lobe, there is a blueshifted emission structure elongated in the north–south direction, which is aligned with HOPS 87. This structure was not considered for calculations of the red outflow parameters.

HOPS 87 is stronger than HOPS 88 in the high-$J$ CO emission (Manoj et al. 2013). It is also brighter than HOPS 88 in the $^{13}\text{CO}$ line (Figure B1(d)). HOPS 87 is associated with OMC 3 MMS 6, the brightest 1.3 mm continuum source in the OMC 2/3 region (Chini et al. 1997). However, the $^{12}\text{CO}$ maps (Figures B1(g) and (h)) may be showing only a hint of an outflow around HOPS 87, and it is too weak to measure the outflow parameters. No clear outflow of HOPS 87 was found in previous studies of single-dish low-$J$ CO observations (Williams et al. 2003; Takahashi et al. 2008). Takahashi & Ho (2012) discovered a compact outflow with interferometric observations.

5.3. HOPS 68

HOPS 68 is a Class I protostar associated with OMC 2 FIR 2 (Mezger et al. 1990; Furlan et al. 2016). It drives a bipolar outflow previously studied in low-$J$ CO lines (Aso et al. 2000; Williams et al. 2003; Takahashi et al. 2008). HOPS 68 has the lowest $T_{\text{bol}}$ among the survey sample. It was detected in fewer than eight far-IR CO lines with PACS and has the lowest rotational temperature among the protostars studied by Manoj et al. (2013).

The $^{12}\text{CO}$ maps of HOPS 68 (Figures B2(g) and (h)) show a prominent bipolar outflow in the north–south direction. It has the second-largest $V_{\text{max}}$ among the target outflows ($\sim 70 \text{ km s}^{-1}$). The kinetic luminosity and outflow force of HOPS 68 are on the high side of the distributions.

5.4. HOPS 370

HOPS 370 is a Class I protostar associated with OMC 2 FIR 3, with a $T_{\text{bol}}$ close to the Class 0–I boundary (Mezger et al. 1990; Furlan et al. 2016). It drives a spectacular bipolar outflow (Aso et al. 2000; Williams et al. 2003; Takahashi et al. 2008). HOPS 370 has the highest $L_{\text{bol}}$ and far-IR CO luminosity among the survey sample. The outflow from HOPS 370 shows the brightest far-IR emission of all of the Orion low-to-intermediate-mass protostars observed by Herschel (Manoj et al. 2013; González-García et al. 2016).

The $^{12}\text{CO}$ maps (Figures B3(g) and (h)) show the bipolar outflow of HOPS 370 flowing in the northeast–southwest direction. Both outflow lobes display redshifted and blueshifted line wings in comparable strengths. This emission pattern suggests that the outflow axis is very close to the plane of the sky, which is consistent with the high inclination angle derived by Furlan et al. (2016). The kinetic luminosity and outflow force of the northeastern (blue) lobe are the largest among the target outflows.

It is difficult to analyze the southwestern outflow lobe of HOPS 370 because of the confusion with other outflows. There are several YSOs in this region (HOPS 64, 108, and 369). The star formation activity of HOPS 64, located 23° southeast of HOPS 370, is not well known, and it exhibits optically thick free–free emission (Osorio et al. 2017). HOPS 108 (FIR 4) is associated with a thermal radio jet and near-IR nebulosity (Reipurth et al. 1999; Takahashi et al. 2008; Osorio et al. 2017). Previous studies suggested that the formation of HOPS 108 may have been triggered by the HOPS 370 outflow (Shimajiri et al. 2008; González-García et al. 2016; Osorio et al. 2017). Though the details are unclear, the velocity structure in this part of the cloud is complicated (Osorio et al. 2017). To the southwest of HOPS 108, there are two radio sources, VLA 15 and VLA 16, indicating other outflow activities of YSOs (Osorio et al. 2017; Tobin et al. 2019). While the redshifted $^{12}\text{CO}$ emission structure (Figures B3(g) and (h)) seems to show the HOPS 370 outflow, the blueshifted emission may be more closely related to the cluster of YSOs in this region.

Near the northeastern outflow lobe of HOPS 370, there is HOPS 66 (MIR 20; Nielbock et al. 2003), located 15° northwest of HOPS 370. Takahashi et al. (2008) reported a jetlike near-IR feature and extended blueshifted $^{12}\text{CO}$ $J = 3 \rightarrow 2$ emission to the west of this object. This outflow can be seen in the $^{13}\text{CO}$ $J = 6 \rightarrow 5$ map (Figure B3(g)). Though this extended blueshifted emission may be associated with HOPS 66, it is hard to distinguish it from the dominant blueshifted emission of HOPS 370. In calculating the outflow parameters of HOPS 370, this emission structure of HOPS 66 was excluded.

5.5. HOPS 368

HOPS 368 is a Class I protostar associated with OMC 2 VLA 13 (Reipurth et al. 1999; Furlan et al. 2016). It drives a relatively compact bipolar outflow (Takahashi et al. 2008). The $^{12}\text{CO}$ maps (Figures B4(g) and (h)) show the bipolar outflow of HOPS 368 flowing in the north–south direction. The outflow velocity is relatively low, and the dynamical time is relatively long. Despite the relatively high bolometric luminosity, the kinetic luminosity and outflow force of HOPS 368 are the smallest among the target outflows.

5.6. HOPS 60

HOPS 60 is a Class 0 protostar associated with OMC 2 FIR 6b (Chini et al. 1997; Furlan et al. 2016). It drives a prominent bipolar outflow (Takahashi et al. 2008).
The $^{12}$CO maps (Figures B5(g) and (h)) show the bipolar outflow of HOPS 60 flowing in the northeast–southwest direction. In addition, there is a blueshifted emission structure near the southern edge of the maps that belongs to the outflow driven by FIR 6c (HOPS 409; Takahashi et al. 2008). The FIR 6c outflow lobe was excluded from the analysis of the HOPS 60 outflow parameters.

In the $^{12}$CO $J = 6 \rightarrow 5$ map (Figure B5(d)), there is yet another emission component $\sim 30^\circ$ south of HOPS 60. This component is associated with FIR 6a. Shimajiri et al. (2009) proposed that the FIR 6a core may be interacting with the FIR 6c outflow.

### 5.7. HOPS 56

HOPS 56 is a Class 0 protostar associated with OMC 2 CSO 33 (Lis et al. 1998; Furlan et al. 2016). Takahashi et al. (2008) categorized the outflow of HOPS 56 as “probable” because there is a directional discrepancy between a near-IR nebulosity and the redshifted $^{12}$CO $J = 3 \rightarrow 2$ emission peak. The redshifted emission structure subtends a large angle from HOPS 56.

The $^{12}$CO $J = 6 \rightarrow 5$ and $J = 7 \rightarrow 6$ maps (Figures B6(g) and (h)) show outflow structures similar to those seen in the $J = 3 \rightarrow 2$ line, which suggests that the redshifted outflow lobe may have a relatively large opening angle. HOPS 57 is located near the redshifted outflow lobe, but there is no known outflow activity of HOPS 57.

### 5.8. HOPS 182

HOPS 182 is a Class 0 protostar associated with L1641N MM1 (Stanke & Williams 2007; Furlan et al. 2016). The L1641N cluster region contains many YSOs and multiple outflows (Fukui et al. 1986; Wilking et al. 1990; Stanke & Williams 2007; Gåfalk & Olofsson 2008). Stanke & Williams (2007) reported that there are two deeply embedded objects, MM1 and MM3, in the cluster center, each of them driving an outflow along a northeast–southwest direction. They suggested that the CO outflow seen in single-dish maps may be driven by MM1, while MM3 drives a well-collimated faint jet. HOPS 181 (mid-IR source 18 of Ali & Noriega-Crespo 2004) drives yet another outflow in the north–south direction (Stanke & Williams 2007). There is no known outflow activity of HOPS 183.

The $^{12}$CO $J = 6 \rightarrow 5$ and $J = 7 \rightarrow 6$ maps (Figures B7(g) and (h)) show the outflow structures in the HOPS 182 region. The well-defined bipolar lobes in the central region belong to the HOPS 182 outflow. The emission structures near the northern and southern edges of the maps belong to the HOPS 181 giant bipolar outflow and are excluded from the calculations of outflow parameters. The kinetic luminosity and outflow force of HOPS 182 are the second-largest among the target outflows.

### 5.9. HOPS 203

HOPS 203 is a Class 0 protostar associated with HH 1/2 VLA 1 (Pravdo et al. 1985; Rodríguez et al. 1990; Reipurth et al. 1993; Furlan et al. 2016) and has the second-lowest $T_{\text{bol}}$ among the survey sample. It drives the HH 1/2/401/402 giant outflow (Figure 1(c)) that extends more than 20° on either side of the driving source (Ogura 1995; Reipurth et al. 2013). The total projected size of this HH complex is 5.9 pc, which is the second-largest HH flow known (Reipurth et al. 1997). The HH 1/2 flow axis may be very close ($< 20^\circ$) to the plane of the sky (Noriega-Crespo et al. 1991; Eisloffel et al. 1994; Correia et al. 1997), which is consistent with the inclination angle of 70° derived from the SED fitting by Furlan et al. (2016). This outflow has been studied extensively in low-J CO lines (Choi & Zhou 1997; Correia et al. 1997; Moro-Martín et al. 1999).

The $^{12}$CO $J = 6 \rightarrow 5$ and $J = 7 \rightarrow 6$ maps (Figures B8(g) and (h)) clearly show the bipolar outflow of HOPS 203 in the northwest–southeast direction. Both outflow lobes display redshifted and blueshifted line wings.

A faint centimeter continuum source, VLA 2, is located at $3^\circ$ from VLA 1 and drives the HH 144 flow to the west (Reipurth et al. 1993). The $^{12}$CO maps (Figures B8(g) and (h)) show a hint of this flow, but it is too weak to derive outflow parameters. HOPS 165 probably drives HH 146 flow to the south (Reipurth et al. 1993), but it is unclear if this flow produces any detectable CO emission.

### 5.10. HOPS 288

HOPS 288 is a Class 0 protostar associated with L1641 S3 MMS 1 (=L1641 S3 IRS; Stanke et al. 2000; Furlan et al. 2016). The bolometric luminosity of HOPS 288 is the second highest among the survey sample. It drives a giant $H_2$/CO outflow (Wilking et al. 1990; Morgan et al. 1991; Stanke et al. 2000; van Kempen et al. 2016). The infrared $H_2$ features are distributed along the bright 4.6 μm emission, showing a point-symmetric variability of flow direction (Figure 1(d)).

Figure B9 shows the mid-J $^{12}$CO spectra and maps of the HOPS 288 region. Both northeastern and southwestern outflow lobes display redshifted and blueshifted line wings in comparable strengths, which is consistent with the $^{12}$CO $J = 2 \rightarrow 1$ maps presented by Wilking et al. (1990). This emission pattern indicates that the outflow opening angle is larger than the angle between the outflow axis and the plane of the sky. This outflow may have a large opening angle owing to the directional variability mentioned in the previous paragraph (also see the discussion in Stanke et al. 2000). Among the target outflows in this work, the kinetic luminosity and outflow force of HOPS 288 are moderate, despite the large bolometric luminosity.

### 6. Summary

Ten protostellar outflows in the OMCs were observed in the $^{12}$CO/$^{13}$CO $J = 6 \rightarrow 5$ and $^{12}$CO $J = 7 \rightarrow 6$ lines with the APEX/CHAMP$^+$ instrument. The target protostars were selected based on the bright far-IR CO lines (Manoj et al. 2013, 2016). Maps were made in the three lines and have an angular resolution of 10$''$.

The target protostars show outflows traced by the $^{12}$CO $J = 6 \rightarrow 5$ and $J = 7 \rightarrow 6$ line wings. For each outflow lobe, parameters such as the maximum velocities, lobe lengths, dynamical timescales, and masses were measured. The properties of the molecular outflows were derived, including the mass transfer rates, kinetic luminosities, and outflow forces.

In addition to the data from the observations presented in this paper, the data of low-luminosity protostars presented by Yıldız et al. (2015) were reanalyzed. The outflow parameters of van Kempen et al. (2016) were also included in the analysis. By combining these data sets, the outflow sample covers a wide range of luminosities, $L_{\text{bol}} = 1.6–520 L_{\odot}$.
The outflow parameters derived from the $^{12}\text{CO} \ J = 6 \rightarrow 5$ line show strong correlations with those from the $J = 3 \rightarrow 2$ line, which suggests that the two lines trace essentially the same outflow component. The outflow kinetic luminosities from the $J = 6 \rightarrow 5$ line and the high-$J$ (far-IR) line-emission luminosities of CO show little correlation, which implies that they trace distinct components of molecular outflows. The low-/mid-$J$ CO line wings and the high-$J$ CO lines are sensitive to the long-term outflow behaviors and short-term accretion activities, respectively. Nevertheless, the underlying energy source may be related because $L_{\text{bol}}$ shows moderate correlations with both $L_{\text{out}}$ and $L^\text{FIR}_{\text{bol}}$.

The correlations between the properties of molecular outflows and protostars were investigated. Similarly to the findings of previous works, the mass outflow rate, outflow force, and kinetic luminosity increase with bolometric luminosity and envelope mass. Power-law fits to the outflow parameters as functions of these protostellar parameters are presented. The strengths of molecular outflows show little correlation with bolometric temperature. The evolution of outflow parameters with $T_{\text{bol}}$ may be complicated.

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### Appendix A

**Outflow Properties of Low-mass Protostars**

The outflow parameters of low-mass protostars were recalculated with the data presented by Yildız et al. (2015) using the method described in Section 3 of this paper. Velocity limits were determined using the $^{12}\text{CO} \ J = 6 \rightarrow 5$ spectra with a 1 km s$^{-1}$ velocity resolution. Table A1 lists the newly determined limits. The systemic velocities and distances were taken from Table 4 of Yildız et al. (2013). For several sources, the protostellar parameters and distances were updated for various reasons, and Table A2 lists the values used in this paper. The outflow parameters were calculated using the $^{12}\text{CO} \ J = 6 \rightarrow 5$ data, corrected for the inclination angles listed in Tables 2 and 3 of Yildız et al. (2015). The outflow properties of 14 protostars are listed in Table A3. There are 23 protostars in the $J = 6 \rightarrow 5$ line sample of Yildız et al. (2015), but nine of them were omitted. The line-wing emission intensities of seven protostars (Ced 110 IRS 4, L723MM, TMC 1A, TMC 1, DK Cha, Oph IRS 63, and RNO 91) are not strong enough to calculate the outflow parameters. Objects TMR 1 and GSS 30

| Source  | $D$ (pc) | $L_{\text{bol}}$ ($L_\odot$) | $T_{\text{bol}}$ (K) | $L^\text{FIR}_{\text{bol}}$ ($\times 10^{33} L_\odot$) |
|---------|---------|-----------------------------|----------------------|---------------------------------|
| BHR 71$^a$ | 200 | 14.8 | 44 | 11.7 |
| Serpens SMM 1$^b$ | 436 | 109.2 | 39 | 153.8 |
| Serpens SMM 4$^b$ | 436 | 6.8 | 26 | 26.6 |
| Serpens SMM 3$^b$ | 436 | 18.3 | 38 | 37.7 |
| B335$^c$ | 164.5 | 1.6 | 39 | 1.4 |
| Elias 29$^d$ | 125 | 20.1 | 387 | 6.3 |

Notes.
- $^a$ For consistency, the $L^\text{FIR}_{\text{bol}}$ (Manoj et al. 2016) is scaled for the distance listed in Kristensen et al. (2012).
- $^b$ The $L_{\text{bol}}$ and $L^\text{FIR}_{\text{bol}}$ (Karska et al. 2013) are scaled for the revised distance from Ortiz-León et al. (2017).
- $^c$ The $L_{\text{bol}}$ (Green et al. 2013) and $L^\text{FIR}_{\text{bol}}$ (Manoj et al. 2016) are scaled for the revised distance from Watson (2020). The $T_{\text{bol}}$ is from Green et al. (2013).
- $^d$ The $L_{\text{bol}}$ and $T_{\text{bol}}$ are from Green et al. (2013). The values in Kristensen et al. (2012) have an unclear origin.

IRS 1 were excluded because the regions around these protostars are too complicated and contain multiple outflows.

The outflow properties reported by Yildız et al. (2015) have a strong bias toward the redshifted outflow. The red-to-blue luminosity ratio is $\log(L_{\text{CO}})/L_{\text{CO}} = 1.1$, on average, with a
The spectra and maps of HOPS 310 are shown in Figure 2, and those of the other protostars are presented here (Figures B1–B9). Details are explained in the caption of Figure 2.
Figure B1. The CO spectra and maps for HOPS 88 (OMC 3 MMS 5).
Figure B2. The CO spectra and maps for HOPS 68 (OMC 2 FIR 2).
Figure B3. The CO spectra and maps for HOPS 370 (OMC 2 FIR 3).
Figure B4. The CO spectra and maps for HOPS 368 (OMC 2 VLA 13).
Figure B5. The CO spectra and maps for HOPS 60 (OMC 2 FIR 6b).
Figure B6. The CO spectra and maps for HOPS 56 (OMC 2 CSO 33).
Figure B7. The CO spectra and maps for HOPS 182 (L1641N MM1).
Figure B8. The CO spectra and maps for HOPS 203 (HH 1/2 VLA 1).
Figure B9. The CO spectra and maps for HOPS 288 (L1641 S3 MMS 1).

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