THE WARM CO GAS ALONG THE UV-HEATED OUTFLOW CAVITY WALLS: A POSSIBLE INTERPRETATION FOR THE HERSCHEL/PACS CO SPECTRA OF EMBEDDED YSOs

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ABSTRACT

A fraction of the mid-\(J (J = 14–13\) to \(J = 24–23\)) CO emission detected by the Herschel/Photodetector Array Camera and Spectrometer observations of embedded young stellar objects (YSOs) has been attributed to the UV-heated outflow cavity walls. We have applied our newly developed self-consistent models of photon-dominated-region (PDR) and non-local-thermal-equilibrium-line Radiative transfer in general Grid to the Herschel far-infrared observations of 27 low-mass YSOs and one intermediate-mass YSO, NGC 7129-FIRS2. When the contribution of the hot component (traced by transitions of \(J > 24\)) is removed, the rotational temperature of the warm component is nearly constant with \(\sim 250\) K. This can be reproduced by the outflow cavity wall \((n > 10^6 \text{ cm}^{-3}, \log G_0/n > -4.5, \log G_0 > 3, T_{\text{gas}} > 300 \text{ K}, \text{ and } X(\text{CO}) > 10^{-5})\) heated by a UV radiation field with a blackbody temperature of 15,000 or 10,000 K. However, a shock model combined with an internal PDR will be required to determine the quantitative contribution of a PDR relative to a shock to the mid-\(J\) CO emission.

Key words: astrochemistry – circumstellar matter – infrared: ISM – methods: numerical – photon-dominated region (PDR) – radiative transfer

Supporting material: figure set

1. INTRODUCTION

Embedded young stellar objects (YSOs) are associated with energetic phenomena: jets, outflows, and high-energy photons emitted by accretion shocks on the surface of protostars and disks. These phenomena determine the physical conditions of the surrounding material, particularly in close proximity to the central object. However, it is difficult to directly detect emission from the warm/hot gas and dust closest to the forming star because of the thick enshrouding envelope.

In this regard, far-infrared (FIR) spectroscopy can be a powerful tool for the study of embedded YSOs because the energetic photons produced by accretion are absorbed and re-emitted in this wavelength regime. FIR spectroscopic observations of 28 low-mass embedded protostars (e.g., Giannini et al. 2001; Nisini et al. 2002; van Dishoeck 2004) were carried out for the first time with the Long Wavelength Spectrometer (Clegg et al. 1996) on board the Infrared Space Observatory (ISO). These observations discovered widespread CO emission arising from rotational states from \(J = 14\) to \(J = 29\) (for NGC 1333-IRAS 4, Giannini et al. 2001; Maret et al. 2002). A Large Velocity Gradient (LVG) analysis of these observations suggests that the FIR CO emission is radiated from the gas with a temperature of a few hundred to \(\sim 1000 \text{ K}\) and a density of \(10^5 \sim 10^6 \text{ cm}^{-3}\) (e.g., Giannini et al. 2001; Nisini et al. 2002; van Dishoeck 2004). A non-dissociative shock is the leading candidate for the heating mechanism producing the high-\(J\) CO emission (e.g., Nisini et al. 2002); however, Ceccarelli et al. (2002) proposed that a super-heated disk surface layer that is exposed to ultraviolet photons could account for the FIR CO emission in Elias 29.

The Herschel Space Observatory (Pilbratt et al. 2010) provides higher spatial resolution and sensitivity when compared to ISO. Furthermore, the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) covers the CO rotational lines from \(J = 14–13\) to \(J = 49–48\) (Herczeg et al. 2012) and has provided a wealth of new observations of energetic gas in protostars. A Herschel open time key program, “Herschel Orion Protostar Survey (HOPS)” observed 22 protostars in Orion. Manoj et al. (2013) noted that these sources span two orders of magnitude in bolometric luminosity \((0.2 L_\odot \leq L_{\text{bol}} \leq 28 L_\odot)\), while their CO rotation diagrams show that the CO emission can be characterized by two thermal components: warm gas with a rotational temperature of \(T_{\text{rot}} \sim 350 \text{ K}\) and hot gas with \(T_{\text{rot}} \sim 700–900 \text{ K}\). The rotational temperature of \(\sim 350 \text{ K}\) appears to be universal in the mid-\(J\) range \((14 \leq J \leq 24)\) and independent of the bolometric luminosity. Additional observations of the CO rotational emission were obtained as part of the Herschel key program: “Water in star-forming regions with Herschel” observed 18 embedded protostars (Karska et al. 2013), and “Dust, Ice, and Gas In Time” observed 30 sources (Green et al. 2013). These sources also have properties similar to those observed by the HOPS program, i.e., all programs found the universal 350 K component in the mid-\(J\) CO ladder.

An LVG analysis indicates that there are two possible explanations for the observed CO emission. One is subthermally excited gas with a high temperature (>1000 K) and low density (<10^6 cm^{-3}; Neufeld 2012; Manoj et al. 2013). In this case, one component can fit the CO emission over the entire PACS range. The other component is thermally excited gas with a high density (>10^6 cm^{-3}) and both warm (\sim 300 K) and hot (700–800 K) temperatures, which are shown in the rotational diagram.

van Kempen et al. (2010a) and Visser et al. (2012) explored the origin of the mid-\(J\) CO emission as arising from the UV-heated gas along the outflow cavity walls (the photon-dominated region, PDR) and small-scale C-type shocks inside the walls. Furthermore, Visser et al. (2012) suggested that the PDR contributes more to the FIR CO emission as the protostar evolves. However, there are caveats in their model; they combined an approximated two-dimensional (2D) PDR model...
and a one-dimensional (1D) shock model, and the UV spectrum for the gas energetics and chemistry was different in the PDR model.

Manoj et al. (2013) argued that the PDR is a minor contributor to the mid-J CO emission based on three points. First, it is difficult for the PDR process to produce a similar gas temperature regardless of the bolometric luminosity, \( L_{\text{bol}} \). The gas temperature in the PDR is roughly proportional to \( L_{\text{UV}}/n \), where \( L_{\text{UV}} \) is the UV luminosity (considered to be proportional to \( L_{\text{bol}} \)) and \( n \) is the gas density. The density at a specific radius is not necessarily correlated with \( L_{\text{bol}} \). As a result, there is no reason to have a similar \( L_{\text{UV}}/n \) over a large range of \( L_{\text{bol}} \). Second, due to the dilution of UV photons, the PDR cannot produce consistent gas conditions over the large radius range required to match the CO mid-J emission. Finally, the resolved spectra of lower-J (\( J \leq 10 \)) CO emission in NGC 1333 (Yldz et al. 2010) show that the contribution of a ”broad” spectral component is consistent with shocked gas and dominates \( J \sim 10-9 \) emission, implying that the PDR provides a minor contribution to the CO emission in PACS range. In addition, Karska et al. (2013) also argued that UV-heated gas is a minor component of the mid-J CO emission because of a strong correlation between the fluxes of CO \( J = 14-13 \) and \( J = 24-23 \) and the flux of \( H_2O \), which traces shocked gas.

However, an internal PDR must exist at some level in the protostellar stage. Furthermore, it may not be negligible because FUV observations toward classical T Tauri stars find that these stars emit UV photons at a few percent of the accretion luminosity (e.g., Herczeg et al. 2002; Yang et al. 2012). These UV photons can affect the physical and chemical properties of exposed gas within the outflow cavity and along the walls (van Kempen et al. 2010a; Visser et al. 2012; Lee et al. 2014b, hereafter Paper I). In this regard, Yldz et al. (2012) used spectrally resolved observations of \(^{13}\)CO \( J = 6-5 \), finding that the narrow emission lines (\( \Delta \nu < 2 \text{ km s}^{-1} \)) toward NGC 1333-IRAS 4A are consistent with emission from UV-heated outflow cavity walls, which encapsulate the broad outflow lines (\( \Delta \nu > 10 \text{ km s}^{-1} \)). They find that the mass of the UV-heated gas is at least comparable to the mass of the outflowing gas. In addition, UV photons produced from accreting protostars are required to explain the emission from ionized hydrides (CH\(^+\) and OH\(^+\)) that are detected with Herschel/HIFI (de Graauw et al. 2010) and are inferred to emit from within 100 AU of the young star (Kristensen et al. 2013). Therefore, a quantitative test with a self-consistent PDR model is required to study the importance of PDR for the mid-J CO transitions in embedded protostellar objects.

We developed a 2D PDR model that self-consistently calculates the gas energetics and chemistry for a given UV spectral type (Paper I). This model was applied to HH46, assuming the Draine interstellar radiation field and a \( T_{\text{eff}} = 1.5 \times 10^4 \) K blackbody radiation field (hereafter BB1.5). We find that the PDR reproduces the observed mid-J CO emission, while the \( T_{\text{eff}} = 10^4 \) K blackbody radiation (hereafter BB1.0) results in a lower rotational temperature in agreement with Visser et al. (2012). According to this model, the mid-J CO emission is radiated from the thermally excited dense CO gas (\( n \sim 10^6 \) cm\(^{-3}\)) with a gas temperature higher than \( \sim 300 \) K and a CO abundance above \( 10^{-7} \).

In this paper, we apply our self-consistent PDR model to a large number of selected embedded protostars and test whether the UV-heated cavity walls can reproduce the universal rotational temperature and fluxes observed in the mid-J CO ladder. We present the properties of our sources in Section 2, and the PDR model and adopted physical parameters are described in Section 3. We present our modeling results in Section 4 and discuss the effect of the physical parameters in Section 5. Finally, we summarize our conclusions in Section 6.

2. SOURCES

In order to test whether the universal rotational temperature can be produced by a PDR along the outflow cavity walls, we have applied our PDR model to the sources that have pre-existing determinations of the density structure in the literature (Jørgensen et al. 2002; Kristensen et al. 2012). In addition, one intermediate-mass embedded protostar, NGC 7129-FIRS2 (Crimier et al. 2010; Fich et al. 2010), has been modeled as an example of a high-luminosity source.

The selected sources (0.8 \( L_\odot \leq L_{\text{bol}} \leq 500 L_\odot \)) are listed in Table 1 and are plotted in the domain of bolometric luminosity versus density at 1000 AU (\( n_{1000 \text{AU}} \); Figure 1). Class 1 sources (shown as circles) generally have lower values of \( n_{1000 \text{AU}} \) than Class 0 sources (squares), as shown in Figure 1. We classify sources as ”compact” and ”extended” depending on the distribution of the CO \( J = 14-13 \) or CO \( J = 16-15 \) emission (Figure 1; ”compact” and ”extended” sources are marked with open and filled symbols, respectively) following the definition of Karska et al. (2013).

The observed and synthesized CO fluxes are represented as the total number of CO molecules emitting in a given J level as follows (Green et al. 2013; Karska et al. 2013):

\[ F_{\text{OBS}}(J) = \frac{4\pi D^2F_J}{h\nu_J A_J}, \]

where \( F_J \) and \( \nu_J \) denote the line flux and the frequency of the CO rotational transition from \( J \) to \( J-1 \), \( D \) is the distance to the source, \( A_J \) is the Einstein coefficient, and \( h \) is Planck’s constant.

Rotational diagrams for our sources are plotted in Figures 2–5. The high-J \( (J>24) \) CO transitions, which produce a high rotational temperature of \( \sim 700-900 \) K, were detected toward most of our sources except NGC 1333-IRAS 2A and TMC1A. This hot component is generally interpreted as emitting from shocked gas as opposed to the UV-heated cavity walls (Visser et al. 2012; Paper I). To determine the potential emission from the PDR, we must first remove the contribution of the hot component from the mid-J CO emission.

We calculate two rotational temperatures from the observed mid-J CO lines. The observed rotational temperature of the Warm component, \( T_{W}(\text{OBS}) \), is linear-fitted from the total observed fluxes, while the Corrected rotational temperature of the Warm component, \( T_{W}(\text{OBS}) \), is derived after subtracting the contribution by the hot component from the total mid-J CO fluxes. For this subtraction, we calculate the mid-J fluxes emerging from the hot component using the rotational temperature of the Hot component derived from the observed high-J CO fluxes at \( J > 24 \) (\( T_{H}(\text{OBS}) \), \( T_{H}(\text{OBS}) \), \( T_{H}(\text{OBS}) \), and \( T_{W}(\text{OBS}) \) for each source are listed in Table 2 and plotted as red, green, and blue lines, respectively, in Figures 2–5.

We classify sources as types H, P, and S. Type H sources, which represent half of our sample, are contaminated significantly by the ”hot” component, so \( T_{H}(\text{OBS}) < T_{W}(\text{OBS}) - 3\sigma_W(\text{OBS}) \), where \( \sigma_W(\text{OBS}) \) is a linear fit error of \( T_{W}(\text{OBS}) \). Type P (“Pure”)
Table 1

| Source        | $D$  | $L_{bol}$ | $T_{bol}$ | $p^b$ | $r_n^b$ | $r_{out}^b$ | $n_{1000\text{ AU}}$ |
|---------------|------|-----------|-----------|-------|---------|------------|---------------------|
|               | (pc) | (K)       | (AU)      |       | (AU)    | (AU)       | (cm$^{-3}$)         |
| L1448-MM      | 232  | 8.4       | 47        | 1.5   | 20.7    | 1.9(4)     | 3.9(6)             |
| NGC 1333-     | 235  | 35.7      | 50        | 1.7   | 35.9    | 1.8(4)     | 1.7(6)             |
| IRAS 2A       |      |           |           |       |         |            |                    |
| NGC 1333-     | 235  | 9.1       | 33        | 1.8   | 33.5    | 3.4(4)     | 6.7(6)             |
| IRAS 4A       |      |           |           |       |         |            |                    |
| NGC 1333-     | 235  | 4.4       | 28        | 1.4   | 33.5    | 2.7(4)     | 5.7(6)             |
| IRAS 4B       |      |           |           |       |         |            |                    |
| L1527         | 140  | 1.9       | 44        | 0.9   | 5.4     | 6.5(3)     | 8.1(5)             |
| Ced110-       | 125  | 0.8       | 56        | 1.4   | 4.1     | 5.7(3)     | 3.9(5)             |
| IRS4          |      |           |           |       |         |            |                    |
| BHR71         | 200  | 14.8      | 44        | 1.7   | 24.8    | 1.4(2)     | 1.8(6)             |
| IRAS15398     | 130  | 1.6       | 52        | 1.4   | 6.2     | 6.2(3)     | 1.6(6)             |
| VLA           |      |           |           |       |         |            |                    |
| 1623-243      |      |           |           |       |         |            |                    |
| L483          | 200  | 10.2      | 49        | 0.9   | 12.5    | 1.3(4)     | 5.1(5)             |
| Ser SM1       | 230  | 1.9       | 26        | 1.3   | 31.0    | 1.6(4)     | 4.1(6)             |
| Ser SM4       | 230  | 1.9       | 26        | 1.0   | 6.8     | 1.1(4)     | 5.4(6)             |
| Ser SM4M      | 230  | 5.1       | 38        | 0.8   | 8.9     | 1.1(4)     | 1.1(6)             |
| L723          | 300  | 3.6       | 39        | 1.2   | 8.4     | 2.4(4)     | 8.0(5)             |
| B33           | 300  | 3.3       | 39        | 1.4   | 9.8     | 1.2(4)     | 1.5(6)             |
| L1157         | 325  | 2.6       | 35        | 1.4   | 4.3     | 1.0(4)     | 7.7(5)             |
| L489          | 140  | 3.8       | 200       | 1.5   | 8.4     | 6.7(3)     | 1.9(5)             |
| L1551-IRS5    | 140  | 24.5      | 105       | 1.8   | 28.9    | 2.6(4)     | 1.2(6)             |
| TMR1          | 140  | 3.8       | 133       | 1.6   | 8.8     | 7.9(3)     | 2.1(5)             |
| TMC1A         | 140  | 2.7       | 118       | 1.6   | 7.7     | 6.9(3)     | 2.2(5)             |
| TMC1          | 140  | 0.9       | 101       | 1.1   | 3.7     | 6.7(3)     | 1.8(5)             |
| HH46          | 450  | 27.9      | 104       | 1.6   | 28.5    | 2.3(4)     | 1.2(6)             |
| DK Cha        | 178  | 35.1      | 591       | 1.6   | 12.0    | 9.6(3)     | 9.2(5)             |
| GSS30-IRS1    | 125  | 14.5      | 138       | 1.6   | 16.2    | 1.6(4)     | 1.7(5)             |
| Elias 29      | 125  | 20.1      | 386       | 1.6   | 16.2    | 1.6(4)     | 8.3(4)             |
| RNO91         | 125  | 2.6       | 340       | 1.2   | 6.6     | 5.9(3)     | 3.3(5)             |
| RC1A-IRSSA    | 130  | 7.1       | 126       | 0.8   | 10.1    | 1.0(4)     | 2.8(5)             |
| NGC 7129-FIRS2 | 1260 | 500       | 200       | 1.5   | 1.4     | 100.0      | 1.8(4)             | 1.0(7) |

Note. Sources above the horizontal line are Class 0, sources below are Class I. Physical parameters ($p, r_n, r_{out}$, and $n_{1000\text{ AU}}$) are adopted from Jørgensen et al. (2002) and Kristensen et al. (2012).

The mid-$J$ CO fluxes, corrected for the hot component, still exhibit a nearly constant rotational temperature with $T_{W}(\text{OBS}) \sim 250$ K, as marked with the solid line in Figure 6 (left panel). The right panel of Figure 6 shows the relative contribution of the warm component to the total mid-$J$ CO fluxes; more than half of the flux for a given mid-$J$ transition are emitted by the warm gas component at $J \leq 21$. The CO number in $J = 14$ from only the warm component $N_{W}(14)$ is correlated with $n_{1000\text{ AU}}$ and $L_{bol}$ (Figure 7). These correlations have been shown in Karska et al. (2013), when $N_{W}(14)$ was calculated from the total flux of $J = 14–13$ emitted by both the warm and hot components.

3. MODEL

3.1. Density Distribution

We assume that the density in the envelope has the power-law distribution of a spherically symmetric sphere, excluding the outflow cavity. For our study, the envelope density structure of each source is determined from previous efforts in the literature (Jørgensen et al. 2002; Kristensen et al. 2012), using the 1D radiative transfer program DUSTY (Ivezic & Elitzur 1997). Within this framework, the outflow cavity is carved out using the function given below in the Cartesian coordinate system (Bruderer et al. 2009a):

$$z = \delta_0 \times \left( x^2 + y^2 \right)^{\alpha/2} \times \left( \frac{1}{10^4 \text{ AU} \tan^2(\alpha/2)} \right) \times \left( x^2 + y^2 \right),$$

where $z$ is the outflow axis and $\alpha$ is the full opening angle at $z = 10^4$ AU. For the density inside the outflow cavity, we adopt the density of shocked gas, $n = 6.3 \times 10^3$ cm$^{-3}$ (Neufeld
et al. 2009), which should be the upper limit for the outflow cavity.

We introduce a new coordinate axis $\delta \equiv z/\sqrt{x^2 + y^2}$ instead of $\theta$ in the spherical coordinate system $(r, \theta)$ as shown in Figure 8. While the $\theta$ coordinate describes a circular conical surface, the $\delta$ coordinate provides a circular paraboloid. Both the PDR and non-local thermal equilibrium line radiative transfer models explore scales ranging from $\sim 10$ to $\sim 10^4$ AU, resolving the very narrow regions near the outflow cavity wall surface where the warm CO gas exists. As the boundary between the outflow cavity and the envelope $(\delta_0$ in Equation (2)) is a point of the $\delta$ coordinate, the $(r, \delta)$ coordinates can simply describe the density profile of thin layers near the surface (see Figure 16 in Paper I). Therefore, we use the $(r, \delta)$ coordinates for all of the procedures except RADMC-3D$^4$ (see below), which does not provide the coordinate.

The opening angle is measured by the modeling of existing molecular line emission maps, for example, of $^{12}$CO rotational transitions (e.g., Arce & Sargent 2006). The emission distribution toward some sources suggests that the opening angle increases with the protostellar evolutionary stage and spreads out from $\sim 10$ to $100$ deg for Class 0 and I sources (Arce & Sargent 2006). However, if the UV-heated outflow cavity walls produce the FIR mid-$J$ CO lines, then they should emerge from the inner dense regions ($n \geq 10^6$ cm$^{-3}$; Paper I; Visser et al. 2012). These regions are within a few arcseconds and are smaller than (or comparable to) the beam sizes of millimeter/sub-millimeter wave radio telescopes, even toward nearby star-forming regions. An additional method for determining the opening angle is to fit the spectral energy distribution using dust continuum models (e.g., Furlan et al. 2008), which are model-dependent. The opening angles derived by the latter method are generally smaller than (or similar to) those determined by the former method. For example, an opening angle of $30^\circ$ is derived for TMC1 via both methods, while the opening angle of L1551-IRS5 is $10^\circ$ and $100^\circ$ according to the SED modeling and the CO map, respectively (Furlan et al. 2008; Arce & Sargent 2006). Therefore, it is hard to define “an” opening angle for a source. As a result, we assume an opening angle of $30^\circ$ for all sources, which does not change the 1D density profile significantly and fits the FIR mid-$J$ CO lines reasonably well compared to other values. In addition, this opening angle produces one of the highest CO fluxes for a given UV luminosity, and thus we can test the contribution of the UV-heated outflow cavity wall to the mid-$J$ CO emission. The effect of the opening angle will be discussed in Section 5.1.

Figure 2. CO rotational diagrams for L1448-MM, NGC 1333-IRAS 2A, NGC 1333-IRAS 4A, NGC 1333-IRAS 4B, L1527, and Ced110-IRS4 in units of total number of detected CO molecules (see Equation (1)) divided by degeneracy, $g$. The open red diamonds indicate the values derived from the Herschel/PACS observations. The red (“Hot” component) and blue lines (“Warm” component) are linear fits to the observed fluxes of the high-$J$ ($E_{up} > 1700$ K) and mid-$J$ ($550$ K $\leq E_{up} \leq 1700$ K) transitions, respectively. The green lines are fitted to the mid-$J$ fluxes after subtracting the contribution of the “Hot” component from the total fluxes. Dotted lines represent the sum of the red and green lines. The open black circles represent the best-fit model to the corrected mid-$J$ CO fluxes, and the purple line represents the linear fit of the best-fit model fluxes. The rotational temperature $T_{rot}$ derived from each color line and the source type (see text) are presented in the upper right of the box.
3.2. PDR Model

We have developed a self-consistent PDR model (Paper I). Our PDR model consists of four parts: the calculation of dust temperature, radiative transfer of UV photons, chemistry, and gas energetics. The dust temperature $T_{\text{dust}}$ is calculated with the dust continuum radiative transfer code RADMC-3D, adopting the dust opacity for average Milky Way dust in dense molecular clouds with $R_V = 5.5$ and $C/H = 42$ ppm in polycyclic aromatic hydrocarbons (PAHs; Draine 2003) for a given density distribution and a given bolometric luminosity, $L_{\text{bol}}$.

In low-mass–classical T Tauri stars, accretion shocks onto the protostar are theorized to produce the observed FUV radiation (Calvet & Gullbring 1998; Ingleby et al. 2011), while for the intermediate-mass Herbig Ae/Be stars the central star itself can also be a FUV radiation source (e.g., Meeus et al. 2012). Bow shocks or small-scale shocks inside the cavity or along the cavity wall can also produce additional local UV photons (Neufeld & Dalgarno 1989; LeFloh et al. 2005).

The FUV radiative transfer is calculated in order to determine the unattenuated FUV strength $G_0$ and average visual extinction $(A_V)$ following the method of van Zadelhoff et al. (2003) and Bruderer et al. (2009a). The FUV radiative transfer is calculated for only one representative wavelength with a photon energy of 9.8 eV in the middle of the 6–13.6 eV FUV band. We then measure the FUV strength $G_0$ in units of the Habing field (ISRF; $\sim 1.6 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$). We adopt the same dust properties used for the calculation of the dust temperature (Draine 2003).

Figure 3. Same as Figure 2 except for BHR71, IRAS15398, VLA 1623-243, L483, Ser SMM1, Ser SMM4, Ser SMM3, L723, and B335.
could be illuminated by the FUV radiation of $\sim$600 ISRF from the shocks in HH 46. In addition, some sources, such as Elias 29, GSS30-IRS1 (Liseau et al. 1999), and RCrA IRS5 (Lindberg et al. 2014) are externally illuminated by nearby bright stars.

In our tests, we assume that the only FUV source is accretion onto the protostar. The FUV spectrum affects the photoelectric heating rate of PAHs and small grains (Spaans et al. 1994) as well as the photodissociation (and photoionization) of species (van Dishoeck et al. 2006). However, because we cannot observe the FUV spectrum directly from the central protostar, we assume that it is similar to that of blackbody radiation of $\sim$15,000 K (BB1.5), which represents the FUV continuum of TW Hya (Herczeg et al. 2002; Yang et al. 2012), and fitted FIR mid-J CO fluxes of HH46 better than blackbody radiation of 10,000 K (BB1.0, Paper I).

FUV observations toward classical T Tauri stars find the UV luminosity integrated from 1250 to 1750 Å ($L_{\text{UV}}^{\text{int}}$) is related to the accretion luminosity $L_{\text{acc}}$ as $\log_{10}L_{\text{UV}}^{\text{int}} = 0.836 \times \log_{10}L_{\text{acc}} - 1.67$ with an accuracy of 0.38 dex (Yang et al. 2012). As the FUV luminosity integrated from 912 to 2050 Å is about 2 times $L_{\text{UV}}^{\text{int}}$ for TW Hya and AU Mic (Herczeg et al. 2002; Yang et al. 2012) and the accretion luminosity dominates the bolometric luminosity during the Class 0 and I stages, we adopt a reference FUV luminosity $L_{\text{UV}}$

$$\log_{10}L_{\text{UV}} = 0.836 \times \log_{10}L_{\text{bol}} - 1.37.$$  

Figure 4. Same as Figure 2 except for L1157, L1489, L1551-IRS5, TMR1, TMC1A, TMC1, HH46, DK Cha, and GSS30-IRS1.
In this paper, $L_{\rm UV}$ is used as the unit of $L_{\rm UV}$.

When the spectrum in the FUV range is similar to BB1.5, UV photons can be radiated from BB1.5 or from the bremsstrahlung free–free emission with a temperature of $\sim 30,000$ K (Nomura & Millar 2005). If all $L_{\rm bol}$ is emitted by either of these mechanisms, then the blackbody radiation and the free–free emission radiate $28$ and $\sim 10\%$ of $L_{\rm bol}$ in the FUV range, respectively. In our model, it is thus difficult for $L_{\rm UV}$ to be larger than $0.28$ $L_{\rm bol}$, which is similar to the observed $1\sigma$ scatter ($5 L_{\rm UV}$) at the lowest $L_{\rm bol}$. Therefore, we assume $5 L_{\rm UV}$ to be the upper limit of $L_{\rm UV}$ in our models.

In our model, the gas-phase chemical reaction network is based on the UMIST2006 database (Woodall et al. 2007) modified by Bruderer et al. (2009b). For photoreaction rates, we have adjusted the attenuation factor, $\gamma$, following the method of Röllig et al. (2013) and calculated the unattenuated photoreaction rate with the photodissociation and photoionization cross sections provided by van Dishoeck et al. (2006). We follow the model of H$_2$ formation on interstellar dust grains via physisorption and chemisorption from Cazaux & Tielens (2002, 2004, 2010) with the sticking coefficient of Hollenbach & McKee (1979). The neutral gas can deplete onto dust grains and evaporate through thermal and non-thermal (photon and cosmic-ray) events. We also consider electron attachment to grain and cation-grain charge transfer. The cosmic-ray ionization rate of H$_2$ is set to be $5 \times 10^{-17}$ s$^{-1}$ (Dalgarno 2006). We let the chemistry evolve for $10^5$ yr.

We consider the important heating and cooling processes described in Röllig et al. (2007). We adjust the photoelectric heating rates of PAHs and small grains (Weingartner & Draine 2001) with the correction factor given by Spaans et al. (1994). We also reduce the H$_2$ vibrational heating and cooling rates excited by the FUV photons because only UV photons in the range of 912–1100 Å can pump H$_2$. We also calculate the H$_2$ formation heating, gas-grain cooling/heating, and atomic and molecular line cooling (for details see Paper I).

The chemistry and gas energetics are calculated iteratively. It is very time-consuming to calculate the chemistry with the full chemical network. In order to reduce the time, a subset of the full chemical network has been adopted for gas energetics. As a check, we compared the 1D PDR models with a small network with the chemical species described in Table 1 of Woitke et al. (2009) to identical models with the full chemical network. We find that the gas temperatures for the two chemical networks are consistent over the range of density and FUV strength relevant to this work. The CO abundances near the surface ($A_V < 1$), however, differ from each other by an order of magnitude. Therefore, the iterative calculation of the gas energetics and chemistry use the small network, and then the chemistry with the full network is calculated with the gas temperature determined using the small network.

### 3.3. Line Radiative Transfer

We have developed a new line Radiative transfer code In general Grid (RIG). For details, refer to Paper I. The most important strength of RIG is the ability to optimize the grid coordinates to a given model. RIG works in any coordinate systems, including Cartesian, cylindrical, spherical, and $(r, \delta)$ coordinates.
coordinates. As described above, the \((r, \delta)\) coordinates are optimal for modeling the envelope with outflow cavity walls, and thus the grid cell number of 300 in these coordinates (30 in \(r\) and 10 in \(\delta\)) provides adequate spatial resolution. The best-fit models with a larger number of grid cells (100 in \(r\) and 30 in \(\delta\)), which is comparable to (in \(r\)) or higher than (in \(\delta\)) the spatial resolutions of the model by Visser et al. (2012), show similar results to the models with 300 grid cells.

Collisional rate coefficients for CO are adopted from the Leiden Atomic and Molecular Database\(^5\) (Schöier et al. 2005) updated by Yang et al. (2010) and Neufeld (2012). Following Visser et al. (2012), we fix the non-thermal Doppler width as 0.8 km s\(^{-1}\) and the velocity distribution as \(v(r) = 2 \text{ km s}^{-1} \sqrt{r/m}/r\) with an inner boundary radius \(r_{\text{in}}\). Because the CO ladders in the PACS wavelength range are generally optically thin (Manoj et al. 2013), the velocity field does not significantly affect the result.

In order to compare to observations, we have synthesized maps of CO spectra, viewed face-on with 0\(\prime\) spatial resolution, using a ray-tracing method; these maps are then used to predict the number of CO molecules emitting in the \(J\) level with Equation (1) at a given pixel. Most of the mid-\(J\) CO line produced by PDRs emit within a depth of \(\sim10\) AU (0\(\prime\) at 100 pc) from the surface of the outflow cavity walls, which can be represented in our model due to the optimized \(\delta\) grid (see Section 4.2). We tested the resolution of 0\(\prime\)05 and found that the difference in simulated fluxes between 0\(\prime\)01 and 0\(\prime\)05 resolutions is less than 2\% in the mid-\(J\) transitions. An edge-on view reduces the mid-\(J\) CO fluxes by up to 25\% as a result of extinction from the dusty envelope. Most synthesized mid-\(J\) CO emission arises within the 9\(\prime\)4 \(\times\) 9\(\prime\)4 central spaxel of PACS (which is a few 1000 AU at the distance of our sources).

\(^{5}\) http://home.strw.leidenuniv.nl/~moldat/
4. RESULT

4.1. Best-fit Models

Rotational diagrams from our best-fit models are plotted as black circles in Figures 2–5. Rotational temperatures derived from the best-fit models $T_{\text{W}}(\text{MODEL})$ are listed in Table 2 and inside each panel of Figures 2–5. Most of our best-fit models reproduce the observed mid-$J$ CO emission for sources with $|T_{\text{W}}(\text{MODEL}) - T_{\text{W}}(\text{OBS})| < 3\sigma_{\text{W}}(\text{OBS})$, except for Ced110-IRS4, VLA 1623-243, and L1551-IRS5. Ced110-IRS4 and L1551-IRS5 have $T_{\text{W}}(\text{OBS}) > 400$ K, and thus these sources might mainly be heated by shocks because the UV-heated cavity wall cannot produce a rotational temperature above 400 K in our models. Although VLA 1623-243 has $T_{\text{W}}(\text{OBS})$ of 347 K, shocks could also be the main contributor to the mid-$J$ CO emission because this source is known to have prominent outflow emission (e.g., Bjerkeli et al. 2012).

Figure 9 shows the best-fit $L_{\text{UV}}$ (in unit of $L_{\odot}^{12}$ CO) versus $L_{\text{bol}}$ of sources. From this analysis, we find that the extended sources have a higher $L_{\text{UV}}$ than the compact sources. Sources with the upper limit of $L_{\text{UV}}$ (NGC 1333-IRAS 4B, Ser SMM4, TMC1, and Elias 29) are all associated with extended emission and our predictions underproduce the mid-$J$ CO fluxes. The UV-heated outflow cavity wall generally radiates the compact emission (see below), and thus the extended emission is more likely to be generated by shocks.

In addition, the sources where we estimate an upper limit to $L_{\text{UV}}$, except for TMC1, have a strong "broad" velocity component in the HIFI $12$CO $J = 10-9$ spectrum (San José-García et al. 2013; Yıldız et al. 2013). Furthermore, the HIFI $12$CO $J = 10-9$ flux is similar to the flux extrapolated from the mid-$J$ lines (see Figure 10). TMC1 also shows a strong outflow detected in the PACS [O I] and [C II] lines (Karska et al. 2013; Lee et al. 2014a). Therefore, in this object, the mid-$J$ CO emission could readily be produced by shocks as opposed to UV radiation.

However, for a given UV luminosity, BB1.0 generates a lower rotational temperature but higher CO fluxes than BB1.5 (Paper I). When a UV luminosity of $5 L_{\odot}^{12}$ CO with BB1.0 is used, we find a better fit for both the rotation temperature and CO fluxes for NGC 1333 IRAS 4B, TMC1, and Elias 29, as shown in Figure 10. However, the CO $J = 14-13$ flux in Ser SMM4 is still lower than the observed one by a factor of two. More than half of the observed CO $J = 14-13$ flux is radiated from the
blue extended (outflow) emission in Ser SMM4 (Dionatos et al. 2013; Karska et al. 2013), and thus PDRs could only reproduce the compact emission near the protostar detected in the central spaxel, if any.

The intermediate-mass embedded class 0 protostar NGC 7129-FIRS2 has \( L_{\text{bol}} = 500 L_\odot \) and stellar mass \( M_* = 5 M_\odot \), which is derived assuming that the source is at the birthline (Eiroa et al. 1998; Fuente et al. 2005). The theoretical model of a protostar with an accretion rate of \( \dot{M} = 10^{-5} M_\odot \text{ yr}^{-1} \) shows that \( L_{\text{acc}} \) dominates the contribution to \( L_{\text{bol}} \) up to about \( 4 M_\odot \) (Palla & Stahler 1991, 1992). For the protostar with \( M_* = 5 M_\odot \) at the birthline, the emission from the surface of the protostar with \( T_{\text{eff}} \sim 10^4 \text{ K} \) is the primary contributor to \( L_{\text{bol}} \) (Palla & Stahler 1991, 1992, 1993), and \( L_{\text{UV}} \) accounts for 7.5\% of \( L_{\text{bol}} \), which is an order of magnitude higher than the best-fit \( L_{\text{UV}} \) (0.5 \( L_{\text{bol}} \)) of the model with BB1.0. Thus, the best-fit \( L_{\text{UV}} \) may indicate that most UV photons radiated from the protostar might be blocked by the dense material located in the vicinity of the central protostar.

When the UV spectrum of BB1.5 is adopted, the outflow cavity wall heated by \( L_{\text{bol}} \) can reproduce the observed mid-J CO emission. This might imply that the accretion luminosity dominates the contribution to \( L_{\text{bol}} \) for NGC 7129-FIRS2 \( (M > 10^{-5} M_\odot \text{ yr}^{-1}) \) and the relation between \( L_{\text{acc}} \) and \( L_{\text{UV}} \) derived from the T Tauri stars could be expanded to even intermediate-mass protostars. More detailed study, and likely higher-resolution observations, are needed to determine which interpretation is adequate for the PACS observation.

According to our models, the UV-heated outflow cavity walls could reproduce the observed “compact” mid-J CO emission with or without the hot shock-heated components in the case where the observed rotational temperature is below 400 K. However, we note that our model provides only a possible explanation for the mid-J CO emission, and a quantitative contribution of the UV-heated outflow cavity wall should be calculated by simultaneous modeling of PDR and shocks.

4.2. Physical and Chemical Structure of the UV-heated Outflow Cavity Wall

Figure 11 shows the physical and chemical properties of the best-fit model for Ser SMM1. The properties are plotted along the horizontal distance, \( \Delta R \), from the surface of the outflow cavity wall for given \( z \) heights, which are marked with horizontal color lines and labels in top left panel of Figure 11. Other panels show the density \( n \) (b), the ratio of unattenuated (attenuated) FUV strength to density \( G_0/n \) (\( G_{\text{dust}}/n \)) (c), dust temperature \( T_{\text{dust}} \) (d), gas temperature \( T_{\text{gas}} \) (e), and CO abundance \( X(\text{CO}) \) (f). The regions emitting the majority of the flux for CO \( J = 24-23 \) (filled circles), \( J = 14-13 \) (open squares), and both transitions (filled squares) are plotted over the layers in the panels.

The ratio of FUV strength to density \( (G_0/n) \) can be used to parameterize the dense gas PDR \( (n \geq 10^4 \text{ cm}^{-3}) \) because the physical and chemical properties are similar for a given \( G_0/n \) (Kaufman et al. 1999, Paper I). More directly, photoelectric heating of PAHs and small grains \( (\propto G_0 n) \) and gas-grain collisional cooling \( (\propto n^2) \) determine \( T_{\text{gas}} \) (see Visser et al. 2012). CO is destroyed by photodissociation \( (\propto G_0 n) \) and forms through two-body reactions \( (\propto n^2) \); dissociative recombination and charge transfer; see Paper I. A higher \( G_0/n \) thus gives a higher \( T_{\text{gas}} \), but lower X(\text{CO}) near the surface.

In low-mass star-forming regions, the power-law index in the density profile is lower than two and \( G_0/n \) increases toward the center. Therefore, as the \( z \) height is lowered (i.e., colors from purple to red in panel (a) of Figure 11), \( T_{\text{gas}} \) increases while X(\text{CO}) decreases near the surface. However, X(\text{CO}) near the
surface increases from \( z = 500 \) AU downward (cyan line in panel (f) of Figure 11) to the equatorial plane (red line). Near log \( G_0/n \sim -3 \), UV photons photodesorb \( \text{H}_2\text{O} \) ice into the gas phase, preventing all oxygen from freezing onto dust grains, and a high \( T_{\text{gas}} > 300 \) K makes the formation rate of \( \text{CO} \) high enough to keep \( X(\text{CO}) \) high in the inner dense regions (see Figure 11) where the FIR mid-\( J \) \( \text{CO} \) lines form (Paper I). Both \( \text{H}_2\text{O} \) photodesorption and the fast \( \text{CO} \) formation at >300 K seem important for the physical and chemical conditions in the embedded phase (see Paper I for the detailed discussion).

We find that most of the mid-\( J \) \( \text{CO} \) fluxes in the best-fit models are produced within specific conditions. The \( \text{CO} J = 24-23 \) line forms in the central spaxel with log \( G_0/n \gtrsim -4.5 \) and log \( G_0 \gtrsim 3 \) for all of our sources (see Figure 11). These regions have a density of \( \log n(\text{cm}^{-3}) \gtrsim 6 \) and a depth from the outflow surface wall of \( \Delta R \lesssim \) a few AU (average visual extinction of \( 0.1 \lesssim \langle A_V \rangle \text{(mag)} \lesssim 1 \)), where \( T_{\text{gas}} \gtrsim 300 \) K and log \( X(\text{CO}) \gtrsim -5 \). The \( \text{CO} J = 14-13 \) line emits from the same gas where \( \text{CO} J = 24-23 \) forms, but also in the gas with \( T_{\text{gas}} \sim 100 \) K, which is located at a higher \( \langle A_V \rangle \) and a larger distance from the protostar.

Although some sources show that the \( \text{CO} J = 14-13 \) emission is radiated from outside the central spaxels (see the blue squares in Figure 11), most of the CO emission is radiated from near the protostar in our models. Therefore, the extended mid-\( J \) \( \text{CO} \) emission cannot be reproduced by the UV-heated gas, and is likely associated with shock-heated gas. In this work, we used the fluxes extracted over the whole PACS spaxels, and thus for the extended sources a higher best-fit \( L_{\text{UV}} \) is required to reproduce the total flux.

5. DISCUSSION

5.1. Effect of Physical Parameters

In order to test the effect of physical parameters, we use the model of L1157, which is a compact source located near the median position of the density and the bolometric luminosity plot (Figure 1). We explore the effect of UV luminosity, opening angle, and power index in the density distribution. We set the standard UV luminosity of the protostar as \( 2.4 L_{\text{Y}} \), which is the best-fit value for L1157.

The effect of \( L_{\text{UV}} \). Figure 12 shows the effect of UV luminosity in the range \( 0.0 \leq L_{\text{UV}}/L_{\text{Y}} \leq 100 \). \( L_{\text{UV}}/L_{\text{Y}} > 10 \) is unrealistic because \( L_{\text{Y}} \) cannot exceed 0.28 \( L_{\text{bol}} \) equivalent to \( L_{\text{UV}}/L_{\text{Y}} = 9 \) for BB1.5 (see Section 3.2), but we test two higher ratios of 50 and 100 to cover a high dynamic range of \( L_{\text{UV}}/n_{1000 \text{AU}} \). A higher protostellar UV luminosity produces a larger number of the CO molecules in a given mid-\( J \) level. Thus, \( T_{\text{rot}} \) increases with \( L_{\text{UV}} \) up to \( L_{\text{UV}} < 10 L_{\text{Y}} \), and then is nearly constant with \( T_{\text{rot}} \sim 300 \) K.

The left panel of Figure 13 shows \( G_0 \) estimated for the surface of the outflow cavity as a function of \( L_{\text{UV}} \). The density
A power-law index is 1.6 and $G_0$ follows the inverse-square law of distance from the protostar, and thus $G_0/n$ increases toward the central source. As mentioned in Section 4.2, a dense region ($\log n \geq 6$) exposed to UV radiation with $\log G_0 \geq 3$ and $\log G_0/n \geq -4.5$ can produce the warm CO gas with $T_{\text{rot}} \sim 300$ K traced by the CO mid-$J$ transitions. As $L_{\text{UV}}$ increases, the region satisfying this condition expands. In addition, the filled circles in the left panel of Figure 13 where the majority of CO $J = 14-13$ emission radiates moves outward. This is because the lowest density satisfying the condition decreases with $L_{\text{UV}}$, and there is more mass in the envelope at lower densities. Furthermore, following them as $L_{\text{UV}}$ increases, the filled circles move horizontally along $\log G_0 \sim 4$ down to $\log n \sim 6.5$. When $L_{\text{UV}}$ is higher than $5 L_{\text{UV}}^\ast$ (yellow line), the largest CO $J = 24-23$ emission is radiated around 1000 AU. The critical density of $J = 24-23$ is $\log n = 7$, and thus CO in lower densities is not thermalized, resulting in decreases of $J = 24-23$ emission in the less dense gas beyond 1000 AU.

The UV-heated cavity walls consist of a lower-temperature gas component with $T_{\text{gas}} \sim 100$ K as well as the warm gas that we are interested in. Therefore, the CO $J = 14-13$ transition also traces the cool gas (Paper I). When $L_{\text{UV}}$ is low, the majority of the CO $J = 14-13$ line emission arises from this cool gas, but the contribution of the warm gas to the CO $J = 14-13$ emission increases with $L_{\text{UV}}$, as shown in the right panel of Figure 13. As a result, $T_{\text{rot}}$ increases with $L_{\text{UV}}$.

However, once $L_{\text{UV}}$ is high enough to populate the CO mid-$J$ levels consistent with $T_{\text{rot}} \sim 300$ K, then it remains at this
higher UV flux of $G_0 = 5$ (red lines in Figure 14), then the gas temperature increases, but the CO abundance decreases at $A_V \sim 0.3$. As a result, the center of emission arises from deeper layers ($A_V \sim 1$). Here, the gas temperature is similar to that of the gas with $A_V \sim 0.3$ under $G_0 = 4$. Thus, there is some similarity in the excitation conditions even within a changing external radiation field.

The effect of opening angle. As the opening angle increases, more UV photons escape and do not interact with the envelope. As a result, at a given UV luminosity, the FUV strength along the wall of a larger outflow cavity decreases, resulting in reduced CO emission and $T_{rot}$ in the PACS range (see dotted lines in Figure 15). As seen in Figure 15, an increase in $L_{UV}$ is required in order to fit the observed fluxes for a wider opening angle. Therefore, our models with an opening angle of 30° require the minimum $L_{UV}$. Thus, the best-fit model with a low $L_{UV}$, assuming a fixed opening angle of 30°, can have an improved solution with a larger opening angle and a higher $L_{UV}$. For L1551-IRSS, a model with an upper limit of $L_{UV} = 5 L_{UV}$ and a large opening angle of 100°, derived from the CO map (Arce & Sargent 2006), provides an improved fit to the data. However, models with different opening angles in Figure 15 will change the dust continuum image and spectral energy distribution. Thus, the density profile should be adjusted when assuming a different opening angle, which is not accounted for in our models.

The effect of the density profile. A variation of the power index changes the amount and concentration of dense gas, as well as $G_0/n$, which could change the overall emission profile. In the case of L1157, the power index in the density profile of L1157 has a minor impact on the mid-J line fluxes as shown in rotational temperature even above this fiducial $L_{UV}$. Exploring this more deeply, the lowest and highest mid-J CO transitions ($J = 14–13$ and $J = 24–23$) are radiated within a narrow temperature range of 200–400 K and 300–600 K, respectively, as shown in Figure 13. This is an intrinsic property of a PDR: UV photons heat the gas but also destroy CO. For example, in the 1D PDR model (Paper I), much of the $J = 24–23$ flux is emitted within gas with $A_V \sim 0.3$ when $\log n = 6.5$ and $\log G_0 = 4$ (blue lines in Figure 14). If this gas is exposed to a

Figure 12. Effect of UV luminosity in the model of L1157. The $L_{UV}$ of the standard model (yellow line) is 2.4 $L_{UV}$ (see Equation (3)). Each color represents the UV luminosity scaled to $L_{UV}$ (see Equation (3)). Color lines indicate the rotational diagrams of models with different UV luminosities, and the observed data are plotted with open diamonds. The rotational temperatures, $T_{rot}$, shown in the top right of the panel are the values fitted to the mid-J CO lines of 550 K $\leq E_{up} \leq$ 1700 K. A vertical dashed line indicates the highest ($J = 24$) levels in the mid-J CO lines, which are relevant to this work. $L_{UV} > 10 L_{UV}$ (thin lines) are tested to cover a high dynamic range of $L_{UV}/n_{1000 AU}$, although they are unrealistic for L1157 (see text).

Figure 13. $G_0$ at the outflow cavity wall surface for given $L_{UV}$ (left) and the cumulative contribution of different gas temperatures to the fluxes of $J = 14–13$ (middle) and $J = 24–23$ (right). The color lines are the same as in Figure 12. The filled circles and open squares in the left panel represent the conditions where most of the emission of $J = 24–23$ and 14–13 is radiated, respectively. The filled circles move along the gray solid arrow as $L_{UV}$ increases. Vertical dotted lines indicate the distance from the protostar. The black dashed lines represent $\log G_0/n = -4.5$ and $\log G_0 = 3$. In the middle and right panels, vertical and horizontal lines indicate $T_{gas} = 300$ K and the cumulative contribution of 0.5, respectively.

Figure 16. The majority of mid-J CO emission arises from gas near 1000 AU (see the left panel of Figure 13) and at this radius changing the power index does not alter the emission appreciably. However, in the case where mid-J emission is generated in gas at far greater distances than 1000 AU, the power index significantly affects the result. For example, TMC1 has a density at 1000 AU similar to that of TMC1A, and a lower $L_{tot}$ than TMC1A only by a factor of three. The power indexes of TMC1 and TMC1A are 1.1 and 1.6, respectively.
The best-fit $L_{\text{UV}}$ (in the unit of $L_{\odot}$) for TMC1 is larger than that for TMC1A by at least an order of magnitude because the lower power index of TMC1 reduces the size of the dense region relevant to the population of mid-$J$ CO levels. Therefore, a higher $L_{\text{UV}}$ is needed to heat the reduced volume and produce the observed mid-$J$ CO emission.

5.2. PDRs as A Candidate Mechanism to Produce Mid-$J$ CO Emission

Manoj et al. (2013) argued that PDRs cannot reproduce the constant $T_{\text{W}}$(OBS) because $T_{\text{gas}}$ is roughly proportional to $L_{\text{UV}}/n_{1000\text{AU}}$. However, in our modeling, $T_{\text{rot}}$ is nearly constant as $\sim 300$ K when $\log L_{\text{UV}}/n_{1000\text{AU}} \geq -6$, as shown in Figure 17. In addition, the variation of $T_{\text{rot}}$ is within $\sim 100$ K at $\log L_{\text{UV}}/n_{1000\text{AU}} < -6$. Therefore, $T_{\text{rot}}$ can be considered nearly constant with a scatter of 100 K when the mid-$J$ CO emission is radiated from the UV-heated outflow cavity walls.

As shown in Figure 11, most sources radiate the mid-$J$ CO emission within $\sim 1000$ AU. Therefore, it is impossible for an internal PDR to account for any extended CO emission. About a half of our sources have compact CO emission (see Table 2). In addition, even extended sources also show that a significant mid-$J$ CO flux (or emission peak) is detected near the protostar (Green et al. 2013; Karska et al. 2013). Thus, it is possible for some portion of the mid-$J$ CO emission to be produced by a PDR, which appears to be the case for lower-$J$ $^{13}$CO lines (Yildz et al. 2012).

$^{12}$CO $J = 10$–9 HIFI data (San José-García et al. 2013; Yildiz et al. 2013) is the highest transition where published spectroscopically resolved data exist, except for Ser SMM1 (Kristensen et al. 2013). According to Yildz et al. (2013), the contribution of the narrow velocity component to the total $J = 10$–9 flux seems to have no correlation with the evolutionary stage and varies from zero to 100% with a median of 42%. In addition, the contribution of the broad velocity component increases as the rotational level ($J \leq 10$) increases (van Kempen et al. 2009b; Yildiz et al. 2012, 2013).

As mentioned by Manoj et al. (2013), it is likely that a broad (shocked) component has a larger contribution to the mid-$J$ CO emission above that seen for $J = 10$–9.

However, a UV-irradiated shock might be a contributor to the FIR line emission toward some embedded protostars (Goicoechea et al. 2012; Kristensen et al. 2013; Lee et al. 2014a). A portion of the outflowing gas exists between the protostar and quiescent outflow cavity walls and, depending on the presence of dust in the cavity, this gas will be irradiated by the accreting star, or perhaps by highly excited H or H$_2$ locally in the gas itself. Thus, although it seems likely that the mid-$J$ emission arises in an outflow, it is possible, or even
probable, that the UV photons are a key additional contributor, beyond the shock itself, to heating outflowing gas.

CO ladder emission must carry a tremendous amount of information on the physical state and evolution of protostars. In gas that is not thermally coupled to dust grains (i.e., in PDR or shock-heated gas), CO emission is the main gas coolant, and thus we are tracing the energy output from star formation. This work and Visser et al. (2012) have shown that an internal PDR can contribute to mid-J CO emission, even in the case without a contribution from shock heating. However, the broad line width detected for resolved CO lines \((J \geq 10)\) implies that this gas is not quiescent, but rather must be entrained in an outflow and subject to shock. Evidence for the presence of UV emission is found in the detection of ions such as CH\(^+\) and OH\(^+\) (Kristensen et al. 2013), which require UV radiation in close proximity to the protostar to be created. Furthermore, the inferred abundance of water vapor in shocked gas (e.g., Santangelo et al. 2014) is below that predicted by shock models requiring some mechanism to reduce the anticipated H\(_2\)O creation in the shock. A likely candidate to reduce the water abundance is UV photodesorption generated by the protostar, or perhaps produced in the shock itself. Thus, we know that both shocks and UV photons are present in this environment and detailed modeling of both, encompassing all of these constraints, will be required to extract the key gas physics operating in the gas near stars at their birth.

6. SUMMARY

We have modeled a UV-heated outflow cavity wall as a mechanism to produce the mid-J CO line emission detected by Herschel/PACS toward protostars. We obtain the following results.

1. The UV-heated outflow cavity walls can reproduce the observed compact FIR mid-J CO emission, except for those sources with rotational temperature above 400 K, alone or when combined with a hot shocked component.
2. The mid-J \((14 \leq J \leq 24)\) CO emission can be radiated from the surface \((0.1 \leq A_V \leq 1)\) of a dense \((n \geq 10^6 \text{cm}^{-3})\) outflow cavity wall with \(\log G_0/n \geq -4.5\) and \(\log G_0 \geq 3\), where \(X(\text{CO}) \geq 10^{-5}\) and \(T_{\text{gas}} \geq 300\) K.
3. Under the above conditions, the H\(_2\)O photodesorption and CO formation rates are high enough to keep CO in the warm gas, resulting in the mid-J CO emission.

Our results could support the result of Visser et al. (2012) and the possibility that the PDR contributes at some level to mid-J CO emission for sources with the UV luminosity derived from the T Tauri stars.

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Figure 17. Ratio of the best-fit UV luminosity to density at 1000 AU \((L_{\text{UV}}/n_{1000\text{AU}}})\) and the rotational temperature of the warm component in the best-fit model \(T_{\text{W}}(\text{MODEL})\). \(T_{\text{W}}(\text{MODEL})\) increases and has a strong correlation with \(L_{\text{UV}}/n_{1000\text{AU}}\) \((r = 0.72\) in the confidence level of 5 sigma) up to \(L_{\text{UV}}/n_{1000\text{AU}} \sim 10^{-6}\) then is nearly constant with \(\sim 300\) K. The gray line and symbols indicate the result of Figure 12. The symbols are the same as in Figure 9.
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