Studying infall in infrared dark clouds with multiple HCO$^+$ transitions

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Abstract We investigate the infall properties in a sample of 11 infrared dark clouds (IRDCs) showing blue-asymmetry signatures in HCO$^+$ $J=1–0$ line profiles. We used JCMT to conduct mapping observations in HCO$^+ J=4–3$ as well as single-point observations in HCO$^+ J=3–2$, towards 23 clumps in these IRDCs. We applied the HILL model to fit these observations and derived infall velocities in the range of 0.5–2.7 km s$^{-1}$, with a median value of 1.0 km s$^{-1}$, and obtained mass accretion rates of 0.5–14 × 10$^{-3}$ $M_{\odot}$ yr$^{-1}$. These values are comparable to those found in massive star forming clumps in later evolutionary stages. These IRDC clumps are more likely to form star clusters. HCO$^+ J=3–2$ and HCO$^+ J=1–0$ were shown to trace infall signatures well in these IRDCs with comparable inferred properties. HCO$^+ J=4–3$, on the other hand, exhibits infall signatures only in a few very massive clumps, due to smaller opacities. No obvious correlation for these clumps was found between infall velocity and the NH$_3$/CCS ratio.

Key words: stars: formation — ISM: clouds — star formation: kinematics and dynamics

1 INTRODUCTION

Mass accumulation by inward gravitational motions is a basic step in models of star formation (e.g. Larson 1969; Anglada et al. 1987; Bonnell et al. 2001; Motte et al. 2018). Infall motions often are revealed in observations with moderate optical depth molecular lines, which display blue-shifted self-absorption dips at frequencies where optically thin lines peak, produced by the temperature gradients of dense cores and the infalling gas (e.g. Walker et al. 1986; Wu & Evans 2003). Multiple transitions of many molecules such as CS, CO, H$_2$CO, HCO$^+$, HCN, CH$_3$CN and C$_3$H$_2$ have been investigated to search for infall signatures in various environments in low mass star forming regions (e.g. Myers et al. 1995; Mardones et al. 1997; Tafalla et al. 1998; Keown et al. 2016), as well as massive star forming regions (e.g. Zhang et al. 1998; Wu & Evans 2003; Fuller et al. 2005; Velusamy et al. 2008; Barnes et al. 2010; Qin et al. 2016).

The comparisons of different tracers including multiple transitions of the same tracer have been made through both observations and simulations, to explore which tracers are more efficient to reveal infall signatures in what kind of sources. Higher-$J$ transitions, such as $J=3–2$ and $J=4–3$, of HCN and HCO$^+$ are considered as good tracers for dense clusters based on their infall asymmetries in lines generated in numerical simulations (Chira et al. 2014). Observationally, HCN $J=3–2$ has been considered as a very good infall tracer in a dense clump sample associated with H$_2$O masers (Wu & Evans 2003). The $J=1–0$
transition of HCN was found to have the strongest infall signatures (Stahler & Yen 2010) in simulations although the line shapes depend on the viewing angle (Smith et al. 2012). Compared to HCN, HCO$^+$ changes less drastically in abundances in chemical models at temperatures ranging from 10 K to 40 K (Vasyunina et al. 2012), which is the temperature range of dark clouds. Thus, HCO$^+$ is potentially better for comparing infall in different star forming environments as it is less affected by chemistry. Among HCO$^+$, the lowest transition, HCO$^+$ $J=1$–0, exhibited the most blue-asymmetric profiles towards a sample of 77 candidate high mass protostellar objects (HMPOs) (Fuller et al. 2005), which is consistent with the results of numerical simulations that HCO$^+$ $J=1$–0 is a better indicator of collapse in high mass star formation (Smith et al. 2013) where the gas is not dense enough to excite the higher-$J$ transitions.

Being cold and dense, infrared dark clouds (IRDCs) are believed to represent the initial conditions of massive star formation and the formation of the associated stellar clusters (e.g. Carey et al. 2000; Rathborne et al. 2006; Peretto & Fuller 2009; Motte et al. 2018). Some pilot HCO$^+$ observations towards two massive IRDCs have revealed that the clumps/cores in there are undergoing rapid collapse (Peretto et al. 2013; Conteras et al. 2018). Considering IRDCs are at an earlier stage than HMPOs or ultracompact HII (UCHII) massive clumps, it raises the question of what molecular or ion line tracers can best probe collapse in these IRDCs? In addition, it is important to understand the properties of infall in the IRDC phase compared with infall in more evolved regions.

Recently, in an HCO$^+$ $J=1$–0 mapping survey towards a sample of 27 IRDCs (Peretto et al. in preparation), a significant fraction presented infall signatures in their line profiles. In this paper, we report our follow-up study on a sub-sample of these IRDCs, all of which show infall signatures in HCO$^+$ $J=1$–0 in at least one clump in the IRDCs. We mapped 11 IRDCs with HCO$^+$ $J=4$–3, and made single-point observations with HCO$^+$ $J=3$–2, towards 23 HCO$^+$ $J=3$–2 peak positions, using the James Clerk Maxwell Telescope (JCMT). The aims of the study are to use multiple HCO$^+$ transitions to fit and constrain models of infall motion, to understand infall properties in IRDCs, and to investigate if higher-$J$ transitions of HCO$^+$ can also probe infall and reveal infall properties well in these HCO$^+$ $J=1$–0 selected IRDCs.

The organization of the rest of the paper is as follows: We describe source selection and observations in Section 2. The observational results and data analysis are presented in Section 3. We discuss infall tracers and infall properties of IRDCs in Section 4, and summarize our conclusions in Section 5.

2 Target Selection and Spectroscopic Observations

The sources in this work are a sub-sample of an Institut de Radioastronomie Millimétrique (IRAM) 30 m HCO$^+$ $J=1$–0 survey towards 27 IRDCs (Peretto et al. in preparation). The parent sample was selected to span a range of geometries and a factor of ~100 in mass ranging from ~200 to ~2$\times10^4$ $M_\odot$, to cover a representative sample of IRDCs. From the parent sample we selected 11 IRDCs that manifest blue asymmetry indicative of infall in HCO$^+$ $J=1$–0 in at least one clump. We made follow-up higher-$J$ HCO$^+$ observations and we fit multiple transitions with models, in order to study infall properties in these candidate infalling IRDCs. The basic information on the sources is listed in Table 1.

All the sources have been mapped in HCO$^+$ $J=1$–0 with the IRAM 30 m telescope (half power beam width (HPBW): 29$''$; $\eta_{mb}=0.75$). Since $N_2H^+$ $J=1$–0 has been found to be in good agreement with $H^{13}CO^+$ $J=1$–0 in both velocity and line width (Fuller et al. 2005), we rely on $N_2H^+$ $J=1$–0, which was observed simultaneously with HCO$^+$ $J=1$–0, to locate the central velocity of the cloud and to identify infall signature for all the HCO$^+$ transitions. The IRAM 30 m observations and data reduction of HCO$^+$ $J=1$–0 and $N_2H^+,J=1$–0 of the 27 IRDCs will be presented in a separated paper (Peretto et al. in preparation).

Eleven IRDCs were mapped in HCO$^+$ $J=4$–3 with the Heterodyne Array Receiver Programme (HARP$^1$) (Bucke et al. 2009) (HPBW: 14$''$; $\eta_{mb}=0.63$) on the 15 m JCMT$^2$ on Mauna Kea, Hawaii during August and September 2016 (Project M16BP081), and August 2017 (Project M17BP087). The Auto-Correlation Spectral Imaging System (ACSIS) spectrometer was employed. Maps of 180$''$ by 180$''$ (except one source SDC18.624, whose map size is 240$''$ by 180$''$) were made with RASTER scans with $T_{avsys}$ ranging from 364 K to 613 K (with an average of 443 K), under weather Band 3 and Band 4 with 0.08 $< T_{225\, \text{GHz}} < 0.20$.

Single-point observations were carried out in HCO$^+$ $J=3$–2 towards the HCO$^+$ $J=4$–3 peak positions

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1 https://www.eaobservatory.org/jcmt/instrumentation/heterodyne/harp/

2 The JCMT is operated by the East Asian Observatory (EAO) on behalf of NAOJ; ASIAA; KASI; CAMS as well as the National Key R&D Program of China (No. 2017YFA0402700). Additional funding support is provided by the STFC and participating universities in the UK and Canada.
with JCMT RxA3m frontend and ACSIS backend (HPBW: 20″; \( \eta_{\text{mb}} = 0.57 \)) from April to June 2018 under Project M18AP073. No H\(^{13}\)CO\(^+\) \(J=3–2\) observations were available due to a low LO current at 260 GHz. The molecule line frequencies are listed in Table 2. Each position was observed in position-switching mode (GRID) for an integration time of 300 s in weather Band 4 (0.12 \(< \tau_{25\text{GHz}} < 0.2\)). An off-position (+600″, +600″) (J2000) from the observed position was also observed. The system temperatures ranged from 778 K to 1356 K, with an average of 988 K. For both the HARP and RxA3m observations, ACSIS was configured to cover 250 MHz wide windows, with 8192 channels in each window, resulting in a velocity resolution of \( \sim 0.02 \text{ km s}^{-1} \) for HARP and \( \sim 0.03 \text{ km s}^{-1} \) for RxA3m. All data for the HARP and RxA3 observations were smoothed with a Gaussian kernel which has full width at half maximum (FWHM) of 5.9 channels, resulting in a velocity resolution of 0.15 km s\(^{-1}\) and 0.20 km s\(^{-1}\) for HARP and RxA3, respectively. The telescope pointing was checked before observing a new source and was checked every 1–1.5 h, by observing one or more calibration sources in CO\((2–1)\) at 234.591 GHz and CO\((3–2)\) at 350.862 GHz for RxA3m and HARP, respectively. The uncertainty in the flux calibration is estimated to be about 10%.

The HARP and RxA3m data reduction were undertaken utilizing the STARLINK (Currie et al. 2014) software packages SMURF, KAPPA and GAIA. Each integration was first visually checked. The data were converted to spectral cubes and baselines were subtracted before being written out as FITS format files using standard STARLINK routines (Jenness et al. 2015).

All data were converted from the antenna temperature scale \( T_A \) to main-beam brightness temperature \( T_{\text{mb}} \), using \( T_{\text{mb}} = T_A / \eta_{\text{mb}} \), where main beam efficiencies are listed in Table 2, as well as the noise levels and the velocity resolutions.

3 RESULTS

3.1 Infall Signature Statistics

We have mapped HCO\(^+\) \(J=4–3\) towards 11 IRDCs, which are presented as a contour map overlaid on the emission image of HCO\(^+\) \(J=1–0\) in Figure A.1 through Figure A.11 in Appendix A. The HCO\(^+\) \(J=4–3\) data have been convolved with the IRAM 30 m beam size. We identified 23 dense clumps based on HCO\(^+\) \(J=4–3\) emission peaks in the maps. These are labeled A through D in the figures. The coordinates of these peaks are tabulated in Table 4.

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### Table 1 Physical Parameters of the Observed IRDCs

| Source Name (hh:mm:ss) (◦′′′) | R.A. (J2000) | Decl. (J2000) | Distance (kpc) | \( V_{\text{LSR}} \) (km s\(^{-1}\)) |
|-----------------------------|-------------|--------------|----------------|-----------------|
| SDC18.624-0.070             | 18:25:10.0  | –12:43:45    | 3.50           | 45.6            |
| SDC18.888-0.476             | 18:27:09.7  | –12:41:32    | 4.38           | 66.3            |
| SDC22.373+0.446             | 18:30:24.5  | –09:10:34    | 3.61           | 53.0            |
| SDC23.367–0.288             | 18:34:53.8  | –08:38:00    | 4.60           | 78.3            |
| SDC24.489–0.689             | 18:38:25.7  | –07:49:36    | 3.28           | 48.1            |
| SDC24.618–0.323             | 18:37:22.4  | –07:32:18    | 3.04           | 43.4            |
| SDC25.166–0.306             | 18:38:13.0  | –07:03:09    | 3.95           | 63.6            |
| SDC28.333+0.063             | 18:42:54.1  | –04:02:30    | 4.56           | 79.3            |
| SDC35.429+0.138             | 18:55:30.4  | +02:17:10    | 4.67           | 77.0            |
| SDC35.527–0.269             | 18:57:08.6  | +02:09:08    | 2.95           | 45.4            |
| SDC35.745+0.147             | 18:56:02.6  | +02:34:14    | 5.11           | 83.4            |

Notes: The coordinates and \( V_{\text{LSR}} \) are taken from Peretto et al. (in preparation). \(^b\)The distances are determined from the Galactic Ring Survey (GRS) (Jackson et al. 2008).

The positions of the HCO\(^+\) \(J=4–3\) peaks generally agree well with HCO\(^+\) \(J=1–0\) peaks. An exception is SDC28.333+0.063, in which HCO\(^+\) \(J=4–3\) has peaks at two positions (B and C in the figure) without corresponding HCO\(^+\) \(J=1–0\) peaks. These two clumps may be very small in size and smoothed out by the much larger beam size in the IRAM 30 m telescope, or these regions may have quite different physical conditions leading to an unusual HCO\(^+\) \(J=4–3\) to HCO\(^+\) \(J=1–0\) ratio.

We present the spectra of all three transitions towards the peak positions in Appendix A. As seen from these spectra, infall signatures can be recognized in most of these clumps, and vary among different transitions. We categorized the profile signatures into five types that suggest different kinematic statuses: (1) double peaks with blue strong, an example can be seen in HCO\(^+\) \(J=3–2\) in SDC18.624–0.070B (see Fig. A.1); (2) a blue profile with a shoulder, e.g., the profile of HCO\(^+\) \(J=4–3\) in SDC18.624–0.070B (see Fig. A.1); (3) symmetric profile, e.g., HCO\(^+\) \(J=3–2\) in SDC18.624–0.070A (see Fig. A.1); (4) a red profile with a shoulder, e.g., HCO\(^+\) \(J=1–0\) in SDC18.888–0.476A (see Fig. A.2); (5) double peaks with red strong, e.g., HCO\(^+\) \(J=3–2\) in SDC18.888–0.476A (see Fig. A.2). We summarize the line profiles of different HCO\(^+\) transitions for the 23 IRDC clumps in Table 3.

A double peak with a stronger blue peak profile is the best infall signature that indicates infall is ongoing and can be fitted to derive the infall properties. A blue peak with a red shoulder is also an infall signature which, although less dramatic, can still be used to derive infall parameters through modeling. Both profiles are called blue profiles. It is clear both from spectra or from Table 3 that HCO\(^+\) \(J=1–0\) has the best performance in revealing infall in these IRDCs, with 12 out of 23 displaying a double peak profile with blue peak strong, and five with a blue peak with a shoulder. This is not surprising given that this sample has a selection bias featuring blue asymmetry in
Excitation temperature is rising along the line of sight and $T_{\text{excitation}}$ at the outer edges of the core is rising along $T_{\text{excitation}}$ profile across the cloud (De Vries & Myers 2005). The HILL model assumes a hill shape excitation temperature profile with five free parameters, which are optical depth $\tau$, infall velocity $V_{\text{in}}$, systematic velocity $V_{\text{LSR}}$, velocity dispersion $\sigma$, and excitation temperature $T_{\text{exc}}$. HILL5 is the HILL model, based on Equation (1), which has been adopted in various objects such as IRDCs (e.g., Conklin et al. 2018), low mass cores (e.g., Maureira et al. 2017) and massive starless clumps (e.g., Calahan et al. 2018).

We applied the HILL5 model to fit $\text{HCO}^+ J=1-0$, 3–2 and 4–3 spectral lines towards the peak positions as listed in Table 4. Fitted lines are plotted in red in Figure A.1 through Figure A.11. The fitted infall velocities are listed in Table 4. We exclude clumps (SDC18.888–0.476A, SDC24.618 and SDC35.429) which have red-asymmetries for all transitions.

In some sources (e.g., SDC25.166–0.306C), although the blue-asymmetry profile looks different for different transitions, the derived infall velocities are similar ($\Delta V_{\text{in}} < 0.2 \text{ km s}^{-1}$). A possible explanation is that the line has different optical depth, as listed in Table 4, which causes differences in the line profiles, even with similar infall velocities.

### 3.2 Infall Velocity Calculations

To derive the infall parameters, we adopted the HILL model (De Vries & Myers 2005) to fit the spectral lines. The HILL model is based on the precursor 'two-layer' model (Myers et al. 1996), which has been adopted in many infall studies, though the 'two-layer' model has been found to underestimate infall velocity by a factor of $\sim 2$ (De Vries & Myers 2005). The HILL model assumes a hill shape excitation temperature profile across the cloud, where the center has the peak excitation temperature $T_P$ (De Vries & Myers 2005). The brightness temperature of the molecular line is

$$\Delta T_B (v) = (J (T_P) - J (T_0)) \left[ (1 - e^{-\tau_f (v)}) / \tau_f (v) \right] - e^{-\tau_f (v)} \left( 1 - e^{-\tau_r (v)} / \tau_r (v) \right) + (J (T_0) - J (T_0)) \left[ 1 - e^{-\tau_r (v)} / \tau_r (v) \right],$$

where $T_B$ is the brightness temperature defined as $T_B = (c^2 / 2 \nu^2 k) I_v$, and $I_v$ is the specific intensity. The excitation temperature at the outer edges of the core is $T_0$. The optical depth $\tau_f$ is the optical depth where the excitation temperature is rising along the line of sight and $\tau_r$ is the opposite, with a velocity dispersion of $\sigma$ for the entire cloud. We developed a Python fitting code which consists of five parameters, i.e., the HILL5 model, based on Equation (1), using Python package LMFIT, which also provides error estimates. HILL5 is the HILL model with five free parameters, which are optical depth $\tau$, infall velocity $V_{\text{in}}$, systematic velocity $V_{\text{LSR}}$, velocity dispersion $\sigma$, and excitation temperature $T_{\text{exc}}$. HILL5 is considered as the most robust model among the HILL models (De Vries & Myers 2005), and has been applied to calculate infall velocities in various objects such as IRDCs (e.g., Conklin et al. 2018), low mass cores (e.g., Maureira et al. 2017) and massive starless clumps (e.g., Calahan et al. 2018).

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### 3.3 Clump Sizes and Line Luminosities from $\text{HCO}^+ J=4-3$ Maps

$\text{HCO}^+ J=4-3$ traces the densest part of the cloud among the three transitions, thus it can be used to define the compact, very dense regions in these IRDCs. We obtained the effective angular diameter ($\theta_{\text{transition}}$) size of the dense clumps by measuring the area of the contour at the intensity which is half of the peak intensity of $\text{HCO}^+ J=4-3$, following the method applied in Wu et al. (2010), with the equation

$$\theta_{\text{transition}} = 2 \left( \frac{A_{1/2}}{\pi} - \frac{\theta_{\text{beam}}^2}{4} \right)^{1/2},$$

where $A_{1/2}$ is the area within the contour of half-peak intensity and $\theta_{\text{beam}}$ is the angular beam size. $R_{\text{transition}}$ is the equivalent spatial radius of the clumps, and is calculated as $R_{\text{transition}} = \theta_{\text{transition}} D / 2$, where $D$ is the distance of the source.

### Table 2: Molecular Line Properties

| Molecular Line  | Frequency (GHz) | Telescope | $n_{\text{mol}}$ | HPBW | $\delta v^a$ (km s$^{-1}$) | Average rms$^a$ (K) | Observation Date |
|-----------------|-----------------|-----------|------------------|------|--------------------------|---------------------|-----------------|
| $\text{HCO}^+ J=1-0$ | 89.18852470 | IRAM 30 m | 0.75 | 29$^a$ | 0.16 | 0.07 | 2013$^a$ |
| $\text{HCO}^+ J=3-2$ | 267.55762590 | JCMT | 0.57 | 20$^a$ | 0.20 | 0.33 | 2018 |
| $\text{HCO}^+ J=4-3$ | 356.73422300 | JCMT | 0.63 | 14$^a$ | 0.15 | 0.25 | 2016, 2017 |

$^a$ Both $\delta v$ and root mean square (rms) are on $T_{\text{mb}}$ scale. All data were smoothed with a Gaussian kernel with FWHM of 5.9 channels. $^b$ The IRAM 30 m observations of $\text{HCO}^+ J=1-0$ were made by Peretto et al. (in prep).

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4 This equation is typeset incorrectly in the Astrophysical Journal in (De Vries & Myers 2005). The correct version can be found in the arXiv version in 2004arXiv: astro-ph/0410748.
5 https://lmfit-py.readthedocs.io/
Table 3 The Numbers of Clump Profile Signatures

| Profile Signatures | HCO⁺ J=1−0 | HCO⁺ J=3−2 | HCO⁺ J=4−3 |
|--------------------|-------------|-------------|-------------|
| Double Peaks with Blue Strong | 12 | 11 | 7 |
| Blue Profile with Shoulder | 5 | 3 | 13 |
| Symmetric | 2 | 4 | 2 |
| Red Profile with Shoulder | 3 | 1 | 1 |
| Double Peaks with Red Strong | 0 | 4 | 2 |

Table 4 Infall Velocities Fitted by HILL at Peak Positions of HCO⁺ J=4−3

| Source Name | R.A.(J2000)/Decl.(J2000) | HCO⁺ J=1−0 (in mm s⁻¹) | HCO⁺ J=3−2 (in mm s⁻¹) | HCO⁺ J=4−3 (in mm s⁻¹) |
|-------------|--------------------------|--------------------------|--------------------------|--------------------------|
| SDC18.624-0.070A | 18:25:18.0 | -12.42.20 | 0.82±0.19 | 1.42±0.19 | 2.60±0.36 |
| SDC18.624-0.070B | 18:25:08.5 | -12.42.55 | 1.33±0.15 | 0.82±0.03 | 7.90±0.01 |
| SDC18.888-0.476A | 18:27.09.7 | -12.41.32 | - | - | - |
| SDC18.888-0.476B | 18:27.07.1 | -12.41.40 | 0.57±0.21 | 1.87±0.07 | 5.03±0.33 |
| SDC22.373+0.446 | 18:30:24.5 | -10.09.34 | 1.07±0.00 | 0.84±0.05 | 2.99±0.01 |
| SDC23.367-0.288A | 18:34:53.9 | -08.38.22 | 1.10±0.31 | 2.45±0.35 | 0.50±0.05 |
| SDC23.367-0.288B | 18:34:52.4 | -08.36.47 | 1.30±0.40 | 1.13±0.21 | 3.17±0.09 |
| SDC24.489-0.698A | 18:38:25.8 | -07.49.36 | 0.95±0.03 | 1.43±0.05 | 4.83±0.02 |
| SDC24.489-0.698B | 18:38:28.4 | -07.49.05 | 1.87±0.14 | 1.24±0.09 | 5.37±0.03 |
| SDC26.618-0.323A | 18:37.22.9 | -07.31.42 | - | - | - |
| SDC26.618-0.323B | 18:37.21.5 | -07.33.20 | - | - | - |

The line luminosity is then calculated as

\[
L' = 23.5 \times 10^{-6} \times D^2 \times \left( \frac{\pi \times \theta_{\text{trans}}^2}{4 \ln 2} \right) \int T_{mb} \ K \ km \ s^{-1},
\]

where \(T_{mb} \ dv\) is the integrated intensity at the peak position, \(D\) is in kpc and \(\theta\) in arcsec (Wu et al. 2010).

The calculated clump angular sizes, spatial sizes \(R\) and line luminosities for HCO⁺ J=4−3 are listed in Table 5.

These IRDC clumps have HCO⁺ J =4−3 sizes ranging from 0.17 pc to 0.73 pc, with a mean size of 0.33 pc and a median size of 0.28 pc. These sizes are comparable to clump sizes of higher-J transitions found in later stages of massive clumps. For example, the half-peak clumps’ sizes of HCN J=3−2 towards some UCHII clumps (Wu et al. 2010) have a mean and median size of 0.32 pc and 0.26 pc, respectively. The derived line luminosity of HCO⁺ J=4−3 is in the range 0.2−18 K km s⁻¹ pc², with a mean and median value of 4.1 K km s⁻¹ pc² and 2.6 K km s⁻¹ pc², respectively.

3.4 Clump Mass and Mass Accretion Rate

Assuming all the mass within the beam is uniformly distributed and contributing to the infall motions and the peak regions are spherical, following Calahan et al. (2018) the mass accretion rate is calculated as

\[
\dot{M} = 4\pi R^2 \rho_{in} \left( \frac{3M \rho_{in}}{M} \right) \left( \frac{M}{1000 M_\odot} \right) \left( \frac{v_{in}}{1 \ \text{km s}^{-1}} \right) \left( \frac{1 \ \text{pc}}{R} \right).
\]

The infall velocities used to calculate the mass accretion rates for these IRDCs are from the modeling of HCO⁺ J=1−0 observations. We rely on the column density maps from Peretto et al. (2016) to calculate the mass then the average volume density of the clumps within the IRAM HCO⁺ J=1−0 beam to match the radius from infall observations, to estimate the mass accretion rates. Peretto et al. (2016) derived the column density maps of the sources from Herschel 160 μm and 250 μm observations obtained as part of the Hi-GAL survey (Molinari et al. 2010).
and they estimate an uncertainty of \( \sim 50\% \) in the column density (Peretto et al. 2016).

The assumption that all mass within the beam will contribute to infall profile could lead to an overestimate of the averaged volume density within the beam due to the foreground and background emission along the line of sight, therefore overestimating the mass accretion rate. The averaged column density within the beam, as well as the derived mass accretion rate of the sources, is listed in Table 5.

Note that the above mass estimated from the column density map within the IRAM beam is a beam-size defined mass. Here we want to estimate the physical mass of these clumps by calculating the total dust masses above 4\( \sigma \) of the Herschel map. Based on the radiative transfer equation, following Hildebrand (1983), the flux density of the dust core is related to its mass in the form of

\[
S_\nu = \kappa_\nu B_\nu(T_d)\Omega \mu m_1 N_{\text{tot}}
\]

\( \times 10^{-3} M_\odot \text{ yr}^{-1} \)

where \( \kappa_\nu \) is the dust opacity at the frequency \( \nu \). \( \Omega \) is the solid angle of the core or selected area. \( B_\nu(T_d) \) is the Planck function of the dust temperature \( T_d \) and \( N_{\text{tot}} \) is the gas column density (mostly HI+H\(_2\)). \( \mu = \)

Table 5 The Derived Parameters of IRDC Clumps

| Source Name       | Clump Size \(^a\) (\( \circ \)) | \( R_{\text{transition}} \) \(^a\) (pc) | Line Luminosity \(^a\) (K km s\(^{-1}\) pc\(^2\)) | \( \int T_{\text{mb, dr}} \) \(^a\) (K km s\(^{-1}\)) | \( \frac{N_{\text{H}_2}}{10^{22} \text{cm}^{-2}} \) | \( M_{\text{H}_2} \) \((M_\odot)\) | \( M_{\text{c}} \) \((\times 10^{-3} M_\odot \text{ yr}^{-1})\) |
|-------------------|--------------------------------|-------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------|-----------------|-----------------|
| SDC18.624–0.070A  | 31                             | 0.26                                | 2.74                                          | 3.97                                          | 4.2                         | 636             | 10.3            |
| SDC18.624–0.070B  | 33                             | 0.28                                | 3.05                                          | 6.76                                          | 4.2                         | 636             | 10.3            |
| SDC18.888–0.476A  | -                              | -                                   | -                                             | -                                             | -                           | -               | -               |
| SDC18.888–0.476B  | 49                             | 0.52                                | 17.64                                         | 12.02                                         | 24.5                        | 3430            | 28.4            |
| SDC22.373+0.446   | 26                             | 0.23                                | 1.22                                          | 3.51                                          | 6.7                         | 564             | 4.8             |
| SDC23.367–0.288A  | 25                             | 0.28                                | 1.16                                          | 2.02                                          | 12.9                        | 1597            | 10.6            |
| SDC23.367–0.288B  | 15                             | 0.17                                | 0.42                                          | 1.46                                          | 1.1                         | 288             | 1.2             |
| SDC24.489–0.689A  | 51                             | 0.41                                | 4.13                                          | 4.35                                          | 8.3                         | 426             | 4.4             |
| SDC24.489–0.689B  | -                              | -                                   | -                                             | -                                             | -                           | -               | -               |
| SDC24.618–0.323A  | 37                             | 0.27                                | 2.35                                          | 5.24                                          | -                           | -               | -               |
| SDC24.618–0.323B  | -                              | -                                   | -                                             | 2.16                                          | -                           | -               | -               |
| SDC25.166–0.306A  | 47                             | 0.45                                | 4.32                                          | 3.00                                          | -                           | -               | -               |
| SDC25.166–0.306B  | -                              | -                                   | -                                             | 1.98                                          | 4.9                         | 734             | 2.1             |
| SDC25.166–0.306C  | -                              | -                                   | -                                             | 1.56                                          | 5.1                         | 830             | 3.1             |
| SDC26.333+0.063A  | 25                             | 0.28                                | 2.04                                          | 4.56                                          | 5.4                         | 420             | 4.8             |
| SDC26.333+0.063B  | 35                             | 0.39                                | 5.90                                          | 6.99                                          | -                           | -               | -               |
| SDC26.333+0.063C  | -                              | -                                   | -                                             | 3.09                                          | 4.1                         | 291             | 5.8             |
| SDC28.333–0.063D  | -                              | -                                   | -                                             | 3.16                                          | 3.7                         | 275             | 19.8            |
| SDC35.429+0.138   | 37                             | 0.42                                | 8.47                                          | 6.67                                          | -                           | -               | -               |
| SDC35.527–0.269A  | 29                             | 0.21                                | 0.51                                          | 2.08                                          | 3.0                         | 280             | 1.8             |
| SDC35.527–0.269B  | 28                             | 0.20                                | 0.49                                          | 1.59                                          | 2.4                         | 248             | 0.9             |
| SDC35.527–0.269C  | 28                             | 0.20                                | 0.23                                          | 0.91                                          | -                           | -               | -               |
| SDC35.745+0.147   | 59                             | 0.73                                | 11.50                                         | 3.79                                          | -                           | -               | -               |

\( a \) The physical parameters are from HCO\(^+\) \( J=4-3 \) observations. The clump size and \( R_{\text{transition}} \) are determined from half peak intensity of HCO\(^+\) \( J=4-3 \) observations. For some sources, the sizes of half intensity contours are smaller than the beam size such that the sources are unresolved. Thus, we cannot calculate their sizes and masses. \( b \) The physical parameters are from Herschel \( 160 \mu m \) and \( 250 \mu m \) observations, see Sect. 3.4 for details. \( c \) The physical parameters are derived from HCO\(^+\) \( J=4-3 \) observations, see Sect. 3.4 for details.

Table 6 Previous Infall Studies

| Targets \(^a\) | Tracer | Method | \( V_{\text{max}} \) Range (K km s\(^{-1}\)) | Mean \( V_{\text{in}} \) (K km s\(^{-1}\)) | Mean \( \dot{M} \) Range \((\times 10^{-3} M_\odot \text{ yr}^{-1})\) | Reference |
|---------------|--------|--------|-------------------------------------------|------------------------------------------|------------------------------------------|-----------|
| HMP0s (22/77) | (1–0)  | two-layer | [0.1, 1.0] | \~ 0.9 | \( [0.2, 1.0] \) | [1] |
| UCHII (9/25)  | (4–5)  | two-layer | [0.1, 1.8] | \~ 0.5 | \( [0.03, 6] \) | [3] |
| UCHII (8/30)  | (3–2)  | two-layer | [0.1, 1.8] | \~ 0.7 | \( [0.5, 2] \) | [4] |
| BGPS clump (6/101) | (1–0) | HILLS | [0.5, 1.8] | \~ 2.4 | \( [0.7, 45.8] \) | [5] |
| Hi-GAL clump (21/213) | (1–0) | two-layer | [0.5, 1.5] | \~ 2.1 | \( [0.5, 2] \) | [6] |
| four IRDCs    | (1–0)  | two-layer | [0.4, 2.4] | \~ 1.0 | \( [2.0, 18.0] \) | [6] |

The references are: [1] Fuller et al. (2005); [2] Klaassen & Wilson (2007); [3] Churchwell et al. (2010); [4] Calahan et al. (2018); [5] Traficante et al. (2018); [6] Giannetti et al. (2015). \( a \) The numbers in parentheses are the numbers of infall candidates versus the total numbers of sources. The infall velocity derived from the two-layer model has been found to be about a factor of 2 smaller than that calculated from the HILLS5 model (De Vries & Myers 2005; Barnes et al. 2010).
2.33 is the average molecular weight, \( m_{\text{H}} \) is the mass of the hydrogen atom and \( \kappa_\nu \) is the dust opacity, which is assumed to be related to the frequency in the form \( \kappa_\nu = \kappa_{230\text{GHz}} (\nu/230\text{GHz})^\beta \). The reference value \( \kappa_{230\text{GHz}} = 0.009 \text{ cm}^2 \text{ g}^{-1} \) is adopted from dust model for the grains with coagulation for \( 10^5 \) yr with accreted ice mantles at a density of \( 10^6 \text{ cm}^{-3} \) (Ossenkopf & Henning 1994). \( D \) is the source distance. In calculation, we used the \( \text{NH}_3 \) kinetic temperature (Xie et al. 2021) to approximate the dust temperature. The total core mass which covers the regions above \( 4 \sigma \) in the dust emission map have been calculated utilizing Equation (5), and the result is displayed in Table 5. The derived masses of these IRDC clumps range from 250 to 3400 \( M_\odot \), with a mean mass of 770 \( M_\odot \) and a median mass of 490 \( M_\odot \). They are massive enough to form massive star clusters.

The mean and median values of the mass accretion rates are \( 7.5 \times 10^{-3} M_\odot \text{ yr}^{-1} \) and \( 4.8 \times 10^{-3} M_\odot \text{ yr}^{-1} \), respectively. These values are slightly larger than those found in later massive star forming regions like HMPOs or UCHII regions, as seen in Table 6. Given that the infall velocity derived from the two-layer model will be underestimated by a factor of 2 compared to the HILL5 model, the mass accretion rates in these IRDCs are not very different from those in HMPOs or UCHII regions.

The Kelvin-Helmholtz timescale, which is the time it takes for a star to radiate away its total kinetic energy, reflects how long a star can sustain its luminosity by gravitational contraction. An empirical form of the Kelvin-Helmholtz timescale \( t_{\text{KH}} \) can be written as (Li 2002)

\[
t_{\text{KH}} \approx 19\text{Myr} \left( \frac{M_*}{M_\odot} \right)^{-2.5},
\]

where \( M_* \) is the stellar mass. For a sufficiently massive star, \( t_{\text{KH}} \) can be too short for a star to even reach the main sequence (Li et al. 2003; Klaassen & Wilson 2007). For example, an 8 \( M_\odot \) stellar mass, the lower end of massive stars, has a Kelvin-Helmholtz timescale of 0.1 Myr. The mass accretion rate has to be high enough to allow mass accumulated within 0.1 Myr to be more than 8 \( M_\odot \), so that the massive star will survive to the main sequence. Our measured accretion rate of \( 5 \times 10^{-3} M_\odot \text{ yr}^{-1} \) in these IRDC clumps corresponds to the infall of \( \sim 500 M_\odot \) in 0.1 Myr. According to Equation (6), for any stellar mass \( M_* \lesssim 26 M_\odot \), the current infall rate can provide enough accretion within its Kelvin-Helmholtz time, but it will be hard for more massive stars to reach the main sequence. Therefore, these IRDC clumps can form massive stars, but are more likely to form star clusters rather than a single massive star.

4 DISCUSSION

4.1 Infall Tracers for IRDCs

Some works have claimed that \( \text{HCO}^+ J=4–3 \) is likely more sensitive to trace infall than \( \text{HCO}^+ J=1–0 \) in massive star forming regions, especially for denser regions (Tsamis et al. 2008; Purcell et al. 2006; Klaassen et al. 2012). While in a survey towards a large sample of HMPOs, \( \text{HCO}^+ J=1–0 \) has been found to have more prominent infall signatures, i.e., double peaks with a self-absorbed dip, than \( \text{HCO}^+ J=4–3 \) lines (Fuller et al. 2005), suggesting lower- \( \beta \) \( \text{HCO}^+ \) transitions could be a better infall tracer in these regions. Very limited such studies have been done on IRDCs (e.g., Wyrowski et al. 2016). Based on our survey with multiple \( \text{HCO}^+ \) lines towards a sample of 23 clumps, we can evaluate their ability to reveal infall in IRDCs.

As seen from Table 3, the surveys with three \( \text{HCO}^+ \) transitions at least imply that in infall candidates selected by \( \text{HCO}^+ J=1–0, \text{HCO}^+ J=4–3 \) is not more sensitive, not even comparable, in detecting infall in IRDCs. These results suggest \( \text{HCO}^+ J=4–3 \) may not be optically thick enough to reveal infall in these IRDCs, as also indicated by the opacity derived from the HILL model in Table 4 and Figure 2.

\( \text{HCO}^+ J=3–2 \) has been found to have comparable ability to \( \text{HCO}^+ J=1–0 \) to study infall in later stages of massive star forming regions like HMPOs (Fuller et al. 2005; Reiter et al. 2011; Klaassen et al. 2012), and we find a similar trend for \( \text{HCO}^+ J=3–2 \) in IRDCs. As well as the line profiles, we also compare the derived infall velocities of the three \( \text{HCO}^+ \) transitions as presented in Table 4. The infall velocities derived from \( \text{HCO}^+ J=1–0 \) are slightly larger than those from \( \text{HCO}^+ J=3–2 \) overall, but the weighted average of both transitions is similar (1.02 \pm 0.03 km s\(^{-1}\)) for \( \text{HCO}^+ J=1–0 \) and 0.89 \pm 0.01 km s\(^{-1}\) for \( \text{HCO}^+ J=3–2 \). This may suggest that throughout the parts or layers in the clump where \( \text{HCO}^+ J=1–0 \) and 3–2 probe, the infall velocity does not change much, agreeing with the hypothesis that infall velocity is consistent within these layers or regions.

The infall velocities of \( \text{HCO}^+ J=4–3 \), on the other hand, are much smaller. The weighted average infall velocity of \( \text{HCO}^+ J=4–3 \) (0.67 \pm 0.05 km s\(^{-1}\)) is more than 1.5 times smaller than what is derived from \( \text{HCO}^+ J=1–0 \), with a similar result being found in another study using the two-layer model towards an IRAS source (Barnes et al. 2010). Excluding the non-fitted and/or negative values in Table 4, the median values of infall velocities for \( \text{HCO}^+ J=1–0 \), 3–2 and 4–3 are 0.97, 0.94 and 0.74 km s\(^{-1}\), respectively. The comparisons between pairs of transitions of \( \text{HCO}^+ \) are depicted in Figure 1, which suggests that
J. J. Xie et al.: Infall in IRDCs with HCO$^+$$^1$

Infall in IRDCs with HCO$^+$

Fig. 1 The infall velocity comparisons among the three transitions: $J=1-0$, $J=3-2$ and $J=4-3$. The diagonal line indicates where the infall velocities are equal. The black marks signify the weighted average of infall velocities.

Fig. 2 The optical depth comparisons among the three transitions: $J=1-0$, $J=3-2$ and $J=4-3$. The diagonal line indicates where the optical depths are equal. The black marks signify the weighted average of optical depths. Despite the scattering of the optical depths of HCO$^+$ $J=3-2$ and HCO$^+$ $J=1-0$, they are similar and both are higher than those of HCO$^+$ $J=4-3$.

The infall velocity of HCO$^+$ $J=3-2$ is comparable to that of HCO$^+$ $J=1-0$, while both are larger than those of HCO$^+$ $J=4-3$. The opacities derived from the HILL5 model for all three transitions are also listed in Table 4, and are compared between every two transitions for each clump in Figure 2. It is clear to see that the opacities calculated from HCO$^+ J=1-0$ and $3-2$ are comparable and both are much higher than the values from HCO$^+ J=4-3$. This is consistent with RADEX (van der Tak et al. 2007) modeling for $10^{4}$–$10^{5}$ cm$^{-3}$ at temperatures from 15 to 30 K. The detailed modeling is beyond the scope of this observational work and will be presented in future works.

4.2 Infall Properties of IRDCs

Different infall tracers, especially lower-$J$ and higher-$J$ HCO$^+$ or HCN transitions, normally trace different parts or layers of dense star forming clumps. For massive clumps at different evolutionary stages, like UCHII regions, HMPOs and IRDCs, we will need different infall tracers to best probe the collapsing regions in the clumps, as argued in Wu & Evans (2003) that the infall profile will best be revealed when the opacity of the source and the critical density of the tracer can be well matched. Therefore, the infall properties may be compared for samples at different evolutionary stages as long as the best infall tracers are used to model the kinematic information of infall.

Under this assumption, we find that the infall velocities of IRDCs obtained in this work are in general consistent with the values in other massive star forming regions. For example, an infall velocity of $\sim$1.5 km s$^{-1}$ for HCO$^+ J=3-2$ was obtained applying the HILL5 model towards an IRDC (Contreras et al. 2018) with mass approximating the mass of SDC23.367-0.288, which has an average infall velocity of $\sim$1.4 km s$^{-1}$. In Table 6, we listed infall velocities as well as mass accretion rates obtained from some other studies towards HMPOs and UCHII regions, to compare with our results. Considering that infall velocities calculated from the two-layer model are generally a factor of 2 less than those obtained from the HILL model, the derived infall velocity and therefore the mass accretion rate of these IRDCs (with a median
The sizes and line luminosities of these IRDC clumps in HCO$^+$+ were identified in HCO$^+$0 survey by Peretto et al. (in prep). A total of 23 clumps IRDCs which present infall line profiles in an HCO$^+$+ were calculated. We summarize our main conclusions as the following:

5 CONCLUSIONS

We summarize our main conclusions as the following:

1. We investigate the infall properties in a sample of 11 IRDCs which present infall line profiles in an HCO$^+$+ survey by Peretto et al. (in prep). A total of 23 clumps were identified in HCO$^+$+ J=1–0 selected sample, while HCO$^+$+ J=3–2 and are more than 1.5 times larger than the values derived from HCO$^+$+ J=4–3.

2. We compare the infall signatures traced by the three transitions of HCO$^+$ towards the peaks of the 23 IRDC clumps and found that HCO$^+$+ J=3–2 can trace infall signature well in this HCO$^+$+ J=1–0 selected sample, while HCO$^+$+ J=4–3 shows the least blue asymmetric profiles in these IRDCs.

3. We employed the HILL model to fit infall parameters based on the three HCO$^+$+ transition profiles for the identified IRDC clumps. The infall velocities derived from HCO$^+$+ J=1–0 range from 0.5 to 2.7 km s$^{-1}$, with a median of 1.0 km s$^{-1}$, which are similar to the values derived from HCO$^+$+ J=3–2 and are more than 1.5 times larger than the values derived from HCO$^+$+ J=4–3.

4. The infall velocities and the mass accretion rates in the IRDC clumps in our survey are comparable to the values found in HMPO and UCHII samples. These IRDC clumps are more likely to form star clusters.

5. No prominent correlation between the infall velocities and the ratio of NH$_3$ column density to CCS column density has been found in this sample.

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Appendix A: OBSERVATIONAL POSITIONS OF RXA3M OF HCO$^+$+ J=3–2 ON THE EMISSION MAP OF HCO$^+$+ J=1–0 WITH HCO$^+$+ J=4–3 CONTOURS

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**Fig. A.1** The integrated intensity map of HCO$^+$ J=1–0 overlaid with HCO$^+$ J=4–3 contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s$^{-1}$ for SDC18.624. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of $\int T_{mb} dv$ for the source. A and B are the observed positions of HCO$^+$ J=3–2. The spectra are fitted with the HILL model. The black emission profiles are from the data, while the red lines represent the fitted profiles. The grey dot at the corner of the emission map represents the IRAM beam size.
The integrated intensity map of HCO\(^+\) \(J=1-0\) overlaid with HCO\(^+\) \(J=4-3\) contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s\(^{-1}\) for SDC18.888. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of \(\int T_{mb} dv\) for the source. A and B are the observed positions of HCO\(^+\) \(J=3-2\). The grey dot at the corner of the emission map represents the IRAM beam size.

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**Fig. A.4** The integrated intensity map of HCO\(^+\) \(J=1-0\) overlaid with HCO\(^+\) \(J=4-3\) contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s\(^{-1}\) for SDC23.367. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of \(\int T_{mb} dv\) for the source. A and B are the observed positions of HCO\(^+\) \(J=3-2\). The grey dot at the corner of the emission map represents the IRAM beam size.

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Fig. A.6 The integrated intensity map of HCO$^+ J=1-0$ overlaid with HCO$^+ J=4-3$ contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s$^{-1}$ for SDC24.618. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of $\int T_{mb} dv$ for the source. A and B are the observed positions of HCO$^+ J=3-2$. The grey dot at the corner of the emission map represents the IRAM beam size.

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The integrated intensity map of HCO$^+$ $J=1$–$0$ overlaid with HCO$^+$ $J=4$–$3$ contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s$^{-1}$ for SDC35.429. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of $\int T_{mb} dv$ for the source. The grey dot at the corner of the emission map represents the IRAM beam size.
Fig. A.10  The integrated intensity map of HCO$^+$ J=1–0 overlaid with HCO$^+$ J=4–3 contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s$^{-1}$ for SDC35.527. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of $\int T_{mb} dv$ for the source. A, B and C are the observed positions of HCO$^+$ J=3–2. The grey dot at the corner of the emission map represents the IRAM beam size.

Fig. A.11  The integrated intensity map of HCO$^+$ J=1–0 overlaid with HCO$^+$ J=4–3 contours at 0.5, 0.8 and 1.0 of the maximum of the integrated intensity in K km s$^{-1}$ for SDC35.745. The maximum of the integrated intensity has been stated in Table 5 as the biggest value of $\int T_{mb} dv$ for the source. The grey dot at the corner of the emission map represents the IRAM beam size.