A Systemic Study of 14 Southern Infrared Dark Clouds with the $\text{N}_2\text{H}^+$, HNC, HCO$^+$, and HCN Lines

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ABSTRACT

We have studied 14 southern infrared dark clouds (IRDCs) using the data taken from the Millimetre Astronomy Legacy Team 90 GHz (MALT90) survey and the GLIMPSE and MIPS GALEX mid-infrared survey of the inner Galaxy. The physical and chemical characteristics of the 14 IRDCs are investigated using $\text{N}_2\text{H}^+(1-0)$, HNC(1-0), HCO$^+(1-0)$, and HCN(1-0) molecular lines. We find that the 14 IRDCs are in different evolutionary stages from the “starless” to the sources with an UCHII region. Three IRDCs are detected to have the star forming activities. The integrated intensity ratios $I_{\text{HCO}^+/\text{HCN}}$, $I_{\text{N}_2\text{H}^+/\text{HCN}}$, and $I_{\text{HNC}/\text{HCN}}$ are all about 1.5, which is different from the previous measurements, suggesting that the integrated intensity ratios may be affected by the cloud environments. The integrated intensities of HNC, HCO$^+$ and HCN show a tight correlation for the 14 IRDCs, implying a close link to the chemical evolution of these three species in the IRDCs. The derived excitation temperature for each IRDC is less than 25 K. We estimate the abundances of the four molecules from $10^{-11}$ to $10^{-9}$, and the average abundance ratios $N_{\text{HNC}}/N_{\text{HCN}} = 1.47 \pm 0.50$, $N_{\text{HNC}}/N_{\text{HCO}^+} = 1.74 \pm 0.22$, and $N_{\text{HCN}}/N_{\text{HCO}^+} = 1.21 \pm 0.41$.

Key words: astrochemistry: abundances — ISM: IRDCs — ISM: clouds — stars: formation — ISM: molecules-ratio lines

1 INTRODUCTION

Infrared dark clouds (IRDCs) are the dark extinction regions of high contrast against the bright Galactic mid-infrared background, discovered by the Midcourse Space Experiment (MSX) (Carey et al. 1998; Egan et al. 1998) and infrared Space Observatory (ISO) surveys (Perault et al. 1996). Simon et al. (2006) identified 10,931 IRDCs candidates using MSX 8.3 $\mu$m data. Jackson et al. (2008) showed that these identified IRDCs are located in the fourth quadrant and first quadrant of the Galaxy at a galactocentric distances of 6 kpc and 5 kpc, respectively. Additionally, Peretto & Fuller (2009) identified 11,303 IRDCs candidates using Spitzer 8 $\mu$m data.

Previous researchers suggested that IRDCs were the cold ($T < 25$ K) and dense ($10^5 \text{ cm}^{-3}$) regions, with a scale of 1~10 pc and a mass of $10^2$~$10^5$ $M_\odot$. Egan et al. (1998), Carey et al. (1998, 2000), Rathborne et al. (2006), and Chambers et al. (2009) proposed that the cores within the IRDCs may be in different phase, from a quiescent to an active, and finally into a red core. The quiescent cores represent the earliest preprotostellar (starless) core phase without infrared signatures, while the active cores have the extended and enhanced 4.5 $\mu$m emission with an embedded 24 $\mu$m emission source. When a core shows the polycyclic aromatic hydrocarbon (PAH) emission at 8 $\mu$m, it is considered to be in the finally red core stage. Furthermore, these detected cores have the strong dust emission from millimetre and submillimetre bands (Lis & Carlstrom 1994; Carey et al. 2000; Redman et al. 2003; Rathborne et al. 2005; Beuther et al. 2005; Rathborne et al. 2005, 2006), and only some cores have embedded protostars, indicating that the IRDCs may represent the earliest observable stage of high-mass star formation. Thus, IRDCs can provide us with an opportunity to study the physical and chemical conditions of massive star-forming processes in the earliest stage.

In this paper, we have analyzed 14 southern IRDCs using $N_2H^+(1-0)$, HNC(1-0), HCO$^+(1-0)$, and HCN(1-0) molecular lines from the Millimetre Astronomy Legacy Team 90 GHz (MALT90) survey (Foster et al. 2011). $N_2H^+$, HNC, HCO$^+$, and HCN are good tracers of dense gases. And $N_2H^+$ is known to be a good tracer of the compact center of the cores. Observations of the molecular lines could provide valuable information on the physical and chemical significance of IRDCs.

2 DATA

2.1 IRDCs selection

Simon et al. (2006) made a 8.3 $\mu$m MSX IRDC catalog containing...
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10,931 IRDC candidates. Combined this catalog with the MALT90 survey, we select 18 southern IRDC candidates, but only 14 of them have N2H+(1-0), HNC(1-0), HCO+(1-0), and HCN(1-0) emission with high signal-noise ratio. These lines are all good tracers of dense gases, but provide slightly different information. N2H+ was more resistant to freeze-out on grains than the carbon-bearing species (Bergin et al. 2001). HNC was particularly prevalent in cold gas (Hirot a et al. 1998). HCO+ often showed infall signatures and outflow wings (Rawlings et al. 2004; Fuller et al. 2005). The main beam brightness temperature scale is made by using the for-2
outflow wings (Rawlings et al. 2004; Fuller et al. 2005). The scope is about 38°
izing high-mass dense cores in the southern sky at 90 GHZ with efficiency. The main beam efficiency at 86 GHZ is 51.8%. IRDCs The data extracted from the Millimetre Astronomy Legacy Team 90 GHz (MALT90), GLIMPSE and MIPSGAL surveys are analyzed toward the 14 southern IRDCs.

MALT90 is a large international project aimed at characterizing high-mass dense cores in the southern sky at 90 GHZ with the Mopra 22-m Telescope. The angular resolution of Mopra Telescope is about 38″. The correction for the line intensities to the main beam brightness temperature scale is made by using the formula Tmb = Tmb / n0, where n0 is the frequency-dependent beam efficiency. The main beam efficiency at 86 GHZ is n0,6GHZ = 0.49, and at 110 GHZ is n0,110GHZ = 0.44 (Lo et al. 2009; Ladd et al. 2005). MALT90 data cubes are downloaded from online archive.

GLIMPSE is a mid-infrared survey of the inner Galaxy performed with the Spitzer Space Telescope. MIPS data is a survey of the same region as GLIMPSE, using the MIPS instrument (24 μm and 70 μm) on Spitzer. We use the mosaiced images of GLIMPSE at Spitzer IRAC 8 μm and MIPSGAL at 24 μm. Spitzer IRAC 8 μm has an angular resolution between 1.5″ and 1.9″ (Fazio et al. 2004; Werner et al. 2004), and the angular resolution of MIPSGAL 24 μm is ≈ 6″.

3 RESULTS

3.1 Spectra

Figures 1-14 show the average spectra of N2H+(1-0), HNC(1-0), HCO+(1-0), and HCN(1-0) of the 14 southern IRDCs, respectively. From each Figure, we see that the N2H+ and HCN lines present the hyperfine structure (HFS), and their velocity components blend with each other. However, the main velocity component (1.23 – 0.12) of N2H+ is detected clearly for most of the IRDCs. The N2H+ and HCN lines are fitted using a HFS fit procedure. The fitting results are presented in Table 1. From Table 1, we can find that the optical depths of the N2H+ lines are less than 1 for all the IRDCs, indicating that the N2H+ line is optically thin in the IRDCs, which agrees with the previous researches. For the HCN line, it is also optically thin, which is inconsistent with the previous studies. Considering the quality of the HCN lines’ data and the unsatisfied HFS fits of the HCN lines, it is probable that we underestimate the optical depths of the HCN lines. The velocity widths of the N2H+ lines are between 1 and 3.2. Calculating the velocity dispersion ΔV of the optically thin N2H+ line causing by thermal motions:

\[ \Delta V_{\text{ther}} = \sqrt{8 \ln(2) T \left( \frac{1}{m_{\text{obs}}} + \frac{1}{<m>} \right)} \]  

where T is the gas kinematic temperature, mobs is the mass of the observed species (29 per amu for N2H+), and <m> is the mean molecular mass (2.3 per amu). For gas with T = 20 K, all the sources have N2H+ line widths ΔV > ΔV_{\text{ther}} ≈ 0.68, i.e., having greater nonthermal rather than thermal motions. We assume that the nonthermal motions in the N2H+ line width may arise from turbulence (Mardones et al. 1997).

In Figures 1-14, the HNC and HCO+ spectra show a wide variety of line profiles including the double peak, a peak and a “shoulder”, a peak skewed to the blue side and single symmetric lines. The HNC and HCO+ lines shapes differ from source to source but are usually similar to each other. The N2H+ line, on the other hand, is Gauss toward almost all the sources. In sources with symmetric HNC and HCO+ lines, their peak velocity lies very close to that of the N2H+ line. In sources with double-peaked HNC and HCO+ lines, the N2H+ peak velocity lies between the two peaks (or between the peak and the shoulder), indicating that the complex HNC and HCO+ line profiles arise from self-absorption at low velocities. The Gauss fit is used for the HNC and HCO+ lines and the fitting results are listed in Table 2.

N2H+(1-0), HNC(1-0), HCO+(1-0), and HCN(1-0) all have much higher critical density (> 106 cm−3) for collisional excitation. Therefore, there are no other N2H+(1-0), HNC(1-0), HCO+(1-0), and HCN(1-0) sources in the line of sight direction. For this reason, we can use the V_{LSR} of the molecules to determine the kinematic distance to each IRDC, according to the rotation curve of Reid et al. (2009), where the Galactic center is R0 = 8.4 ± 0.6 kpc and a circular rotation speed is Q0 = 254 ± 16 km s−1. Therefore, four far and four near kinematic distances are obtained for each IRDC. The calculating results are in Tables 1-2. Since IRDCs are perceived as dark extinction features against the Galactic background, it is reasonable to assume that all IRDCs are located at the near kinematic distances. Under this assumption, we can obtain the average kinematic distance and its corresponding error from the four molecules for every IRDC. Here, we do not consider the errors resulting from the uncertainties of positions and the rotation curve. The final results are listed in Table 3.

3.2 The mm and infrared emission in the IRDCs

Figures 1-14 show also the diagrams of N2H+, HNC, HCO+ and HCN integrated intensity superimposing on the Spitzer IRAC 8 μm and MIPSGAL 24 μm emission images for every IRDC. The integrated intensities are calculated for each line in the same velocity range presented in Tables 1-2 for each IRDC. Comparing the IR emission of each IRDC, 14 IRDCs may be divided into different evolutionary stages, from the “starless” to the sources with strong 8 μm emission. From Figures 1-14, we find that the HNC and N2H+ emission both match the silhouettes of IRDCs presented by 8 μm extinction. Hence, HNC and N2H+ molecules can be used to study the morphology of IRDCs in different stages.

IRDC G003.399-00.399 - In Figure 1, the emission of N2H+ and HNC lines show a similar morphology with a single core, but which are different from that of HCO+ and HCN. There are 24 μm and 8 μm emission sources close to the peak of N2H+ emission.

IRDC G003.436-00.572 - In Figure 2, the integrated intensity maps of N2H+(1-0), HNC(1-0), HCO+(1-0), and HCN(1-0) lines all show a morphology extended from south-east to north-
but we cannot see the obvious IR emission. This IRDC seems to be a "starless".

IRDC G10.402-0.020 and IRDC G10.990-0.083 - From Figure 3 and Figure 4, we can see that both IRDCs present elongated structures in all the molecular emission, but have different extended directions. For IRDC G10.402-0.020, the integrated intensity map of N$_2$H$^+$ (1-0) show two cores, while IRDC G10.990-0.083 contains three compact cores. At the same time, the spectral profiles of both IRDCs have double peaks in HNC and HCO$^+$ lines, while the optical thin line N$_2$H$^+$ (1-0) has a single peak. An 24 $\mu$m emission source is close to the peak of the molecular emission in both IRDCs.

**Table 1. The physical parameters for molecular lines N$_2$H$^+$ and HCN.** And all the parameters are averaged on the pixels with the integrated intensity $> 5\sigma$ and intensity $> 3\sigma$.

| source | l | b | molecular line | $T_{abs}$ (K) | $V_{LSR}$ (km/s) | Width (km/s) | $\tau$ | $\int T_{mb}$ dV (K km/s$^2$) | Integrated range (K km/s$^2$) | $\Delta V_{LSR}$ (km/s) | $\Delta T_{mb}$ (K) |
|--------|---|---|----------------|---------------|-----------------|-------------|--------|---------------------|---------------------|---------------------|-----------------|
| G003.399-0.399 | 3.310 | -0.398 | N$_2$H$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HCO$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | H$_2$O | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HNC | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HCO$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |

**Table 2. The physical parameters for molecular lines HNC and HCO$^+$.** And all the parameters are averaged on the pixels with the integrated intensity $> 5\sigma$ and intensity $> 3\sigma$.

| source | l | b | molecular line | $T_{abs}$ (K) | $V_{LSR}$ (km/s) | Width (km/s) | $\tau$ | $\int T_{mb}$ dV (K km/s$^2$) | Integrated range (K km/s$^2$) | $\Delta V_{LSR}$ (km/s) | $\Delta T_{mb}$ (K) |
|--------|---|---|----------------|---------------|-----------------|-------------|--------|---------------------|---------------------|---------------------|-----------------|
| G003.399-0.399 | 3.310 | -0.398 | N$_2$H$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HCO$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | H$_2$O | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HNC | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |
| 3.310 | -0.398 | HCO$^+$ | 0.17 | 0.615 | 0.20 | 2.08 | 0.53 | 0.10 | 0.03 | 4.11 | 0.29 | 14.29 | 2.88 |

**IRDC G308.121-00.337 - In the diagrams of Figure 5, a north-east elongated and compact structure is showed in the four molecular emission, which contains two cores. An 8 $\mu$m emission source is close to the peak of N$_2$H$^+$ emission. The spectra of HNC and HCO$^+$ exhibit the asymmetric profile.**

**IRDC G317.701+0.110 - A compact core and an extended core are showed in the integrated intensity map of N$_2$H$^+$ and HNC lines in Figure 6. At the center of the compact core, there are obvious emission at 24 $\mu$m and 8 $\mu$m, here we do not detect the emission of the HCN line in this IRDC.**

**IRDC G321.756+0.029 - Figure 7 shows a compact core elongating from SE to NW in the four molecular emission.**

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seems that there are no 24 $\mu$m and 8 $\mu$m emission in the IRDC G321.756+00.029.

**4 DISCUSSION**

4.1 infall and outflow

For self-absorbed optically thick lines, the classical signature of infall is a double-peaked profile with the blueshifted peak being stronger, or a line asymmetry with the peak skewed to the blue side, while optically thin lines should show a single velocity component peaked at the line center. In section 3.2, some IRDCs present blue profiles. In order to provide a strong evidence on whether these sources have the infall motion, we plot the map grids of HCO$^+$(-1-0) for each IRDCs and find only three IRDCs (IRDC G331.035-00.418, IRDC G331.708+00.583 and IRDC G341.942-00.167) may have the infall motions. Figures 15-16 show the map grids towards the three IRDCs, which seems to show the infall features in the whole mapping observations. However, in order to affirm that the spectra in the mappings really show the infall signatures, we extract the molecular lines from two positions (In Figures 15-16). In every diagram of the spectra, the optically thin N$_2$H$^+$ line is plotted in black color, while the optically thick HNC and HCO$^+$ lines are presented in green and blue, respectively. The black dash lines and the red dash lines mark the positions of the V$_{LSR}$ of N$_2$H$^+$ line and the absorption dip of optically thick lines, respectively. From the mappings and the spectra in Figures 15-16, these three IRDCs may have the infall motions in the large-scaled regions. We estimate the extent of the infall signature to be up to $2 \times 2$ arcmin$^2$ (at least 2.11 pc for IRDC G331.035-00.418, 1.10 pc for IRDC G331.708+00.583 and 1.40 pc for IRDC G341.942-00.167). In addition, for IRDC G331.708+00.583, Cyganowski et al. (2008) detected it as an outflow candidate and Yu & Wang (2012) found that it has two outflows, corresponding to the two cores in the cloud. At the same time, for IRDC G331.035-00.418 and IRDC G341.942-00.167, we plot their P-V diagrams and do not find the outflow signatures. Infall and outflow both are the signs of star forming. Hence, we suggest that IRDC G331.035-00.418, IRDC G341.942-00.167 and IRDC G331.708+00.583 are forming stars, while other IRDCs without the star-forming activity may be in much earlier stage.

4.2 The integrated intensity

Ratios of the average integrated intensity of N$_2$H$^+$, HNC and HCO$^+$ to HCN for each IRDC are presented in Table 3. Considering the accuracy of the ratios, we chose the pixels with the inte-

| Source            | $I_{N_2H^+}/HCN$ | $I_{HNC}/HCN$ | $I_{HCO^+}/HCN$ | $I_{HCN}/HCN$ | $d$(kpc)     |
|-------------------|------------------|---------------|-----------------|---------------|---------------|
| G003.399-00.399    | 2.16±0.30        | 1.71±0.24     | 1.28±0.20       | 0.78±0.12     | 2.52±0.04     |
| G003.438-00.572    | 1.65±0.24        | 1.58±0.24     | 1.01±0.18       | 0.99±0.18     | 1.10±0.30     |
| G010.402-00.202    | 1.68±0.19        | 1.50±0.18     | 1.71±0.20       | 0.58±0.07     | 1.74±0.04     |
| G010.990-00.083    | 2.85±0.44        | 2.31±0.36     | 1.50±0.26       | 0.66±0.12     | 3.23±0.05     |
| G308.121-00.152    | 1.21±0.16        | 1.68±0.19     | 1.97±0.22       | 0.51±0.06     | 3.64±0.03     |
| G317.701+00.110    | 2.63±0.20        | 2.18±0.17     | 2.54±0.44       | 0.43±0.08     | 2.58±0.05     |
| G321.756+00.029    | 1.29±0.13        | 1.28±0.14     | 1.59±0.16       | 0.63±0.06     | 1.96±0.01     |
| G331.035-00.418    | 0.75±0.04        | 0.86±0.05     | 1.37±0.06       | 0.73±0.03     | 3.63±0.03     |
| G331.708+00.583    | 2.97±0.23        | 1.21±0.11     | 1.23±0.12       | 0.81±0.08     | 3.79±0.02     |
| G334.198-00.202    | 2.20±0.35        | 2.06±0.33     | 1.38±0.25       | 0.72±0.13     | 3.02±0.04     |
| G337.764-00.338    | 2.37±0.26        | 2.53±0.28     | 1.66±0.20       | 0.60±0.07     | 2.87±0.03     |
| G341.942-00.167    | 1.22±0.07        | 1.23±0.07     | 1.45±0.08       | 0.69±0.04     | 3.22±0.05     |
| G344.726-00.541    | 1.89±0.36        | 1.95±0.36     | 2.02±0.38       | 0.50±0.09     | 2.92±0.01     |
| G345.556+00.026    | 1.25±0.20        | 1.31±0.21     | 1.41±0.22       | 0.71±0.11     | 1.80±0.02     |
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grated intensity $> 5\sigma$ and the intensity $> 3\sigma$ for $\text{N}_2\text{H}^+$, HNC, HCO$^+$, and HCN. From Table 3, we find that all $I_{\text{HCO}^+/\text{HCN}}, I_{\text{N}_2\text{H}^+/\text{HCN}}$, and $I_{\text{HNC}/\text{HCN}}$ are almost constant with around 1.5 in the error scales for all the IRDCs, implying that the integrated intensity ratios seem not to change with the evolution of IRDCs. Hsieh et al. (2012) shows that $I_{\text{HNC}/\text{HCO}^+}$ is 1.67 ± 0.83 in the starburst Ring and 2.22 ± 0.50 in the Syfert nucleus. It is noticeable to us that our $I_{\text{HNC}/\text{HCO}^+}$ of each IRDC is very different from those of the starburst Ring and the Syfert nucleus, indicating that the integrated intensity ratios probably depend on the cloud environments.

Figure 17 shows a relationship of the average integrated intensity between HNC, HCO$^+$ lines and HCN line for the 14 IRDCs. We find a tight correlation between HCO$^+$ and HCN ($r = 0.98$), and a linear fitting relationship:  

$$I_{\text{HCO}^+} = (1.32 ± 0.04) \times I_{\text{HCN}} + (0.49 ± 0.10)$$  (2)

A very high correlation coefficient $r = 0.90$ is also found for the average integrated intensity of HNC and HCN lines (Figure 17) for the 14 IRDCs. The linear fitting result is  

$$I_{\text{HNC}} = (0.77 ± 0.03) \times I_{\text{HCN}} + (1.75 ± 0.10)$$  (3)

The results above indicate that there is a close relationship for the three species during the process of their chemical evolution in the IRDCs. According to this argument, it will contribute to determine the dominated chemistry model in the IRDCs through the numerical simulation. From Figure 17, we also find that IRDCs G331.035-00.418 and G341.942-00.167 have larger integrated intensity of HNC, HCO$^+$, and HCN, which are associated with an UCHII region. It seems that the UV radiation field has an influence on the chemistry of HNC, HCO$^+$, and HCN molecules in the IRDCs, but we need more data to examine this result.

4.3 Column density and the relationships between the abundance ratios and distances

4.3.1 Derivation of physical parameters

Under an assumption of local thermodynamic equilibrium (LTE), the total column density, $N$, of the molecule can be derived from the following formula (Scoville et al. 1986).

$$N = 10^5 \times \frac{3k^2}{4\pi \mu^2 v^2} \exp \left( \frac{\nu J}{2kT_{\text{ex}}} \right) \frac{h\nu/6k(J+1)}{\exp(-h\nu/kT_{\text{ex}})} \int \frac{T_{\text{mb}} dv}{1 - e^{-\tau v}}$$  (4)

where $k$ is the Boltzmann constant, $\mu$ is the Planck constant, $v$ is the permanent dipole moment of the molecule and $J$ is the rotational quantum number of the lower state. Here the permanent dipole moment $\mu$ of $\text{N}_2\text{H}^+$, HNC, HCO$^+$ and HCN molecules are 3.40, 3.05, 3.90, and 2.985 (Muller et al. 2001, 2005), respectively. $\nu$ is the transition frequency, $T_{\text{ex}}$ is the excitation temperature, $T_{\text{mb}}$ is the main beam brightness temperature which we get from the Gauss transition frequency, $T_{\text{bg}}$ is the background temperature, and $J(T)$ is defined by  

$$J(T) = \frac{h\nu}{k} \exp \left( \frac{\nu}{h\nu/kT_{\text{ex}}} \right) - 1$$  (6)

According to equation (5) and equation (6), we can derive $T_{\text{ex}}$ and $\tau_v$ as below:  

$$T_{\text{ex}} = \frac{h\nu}{k} \left( \ln \left( 1 + \frac{h\nu}{k} \frac{T_{\text{mb}}}{f(1-\exp(-\tau v))} + J(T_{\text{bg}})^{-1} \right) \right)^{-1}$$  (7)

$$\tau_v = -\ln \left( 1 - \frac{T_{\text{mb}}}{f} \left( J(T_{\text{ex}}) - J(T_{\text{bg}})^{-1} \right) \right)$$  (8)

So $T_{\text{ex}}$ for $\text{N}_2\text{H}^+$ and HCN can be obtained from equation (7). But for HNC and HCO$^+$, we assume that they have the same excitation temperature to HCN, because they show a tight correlation in their integrated intensity. Then the optical depth $\tau_v$ of HNC and HCO$^+$ can be derived from equation (8). $T_{\text{ex}}$ and $\tau_v$ of the four molecules are showed in Table 1 and Table 2. Then we can calculate the column densities of $\text{N}_2\text{H}^+$, HNC, HCO$^+$ and HCN using equation (4), the results are in Table 4.

4.3.2 The Column density of $\text{N}_2\text{H}^+$, HNC, HCO$^+$, HCN and abundance ratios

Using the equations in section 4.3.1, all the physical parameters are derived and presented in Tables 1-4. From Table 1 and Table 2, we find that $T_{\text{ex}} < 25 K$ and the optical depths of the four molecular lines are less than 1 for all the IRDCs. Considering the fact that HNC, HCO$^+$ and HNC lines should be optically thick, their optical depths in our results are probably underestimated. The derived column densities for the four species and the abundance ratios $N_{\text{HNC}}/N_{\text{HCN}}$, $N_{\text{HCO}^+}/N_{\text{HCN}}$, $N_{\text{HNC}}/N_{\text{HCO}^+}$ are listed in Table 4. The uncertainties of the column densities include all the errors caused by $T_{\text{ex}}$, $\tau_v$ and the integrated intensities. From Table 4, we find that the column densities of the four molecules spread over the range of $10^{12} \sim 10^{13}$. Then we estimate that the abundances of the four molecules using the typical H$_2$ column density ($0.9 \sim 4.6) \times 10^{22}$ cm$^{-2}$ in southern infrared dark clouds (Vasyunina et al. 2009) are in the range of $10^{-11} \sim 10^{-9}$, which are consistent with the results of Vasyunina et al. (2011) and Zinchenko et al. (2009) for $\text{N}_2\text{H}^+$, HNC and HCN molecules, but nearly one order lower for HCO$^+$ molecule, even over two order lower than the results of Sanhueza et al. (2012). This abundant difference of HCO$^+$ molecule is mainly caused by the optical depth. HCO$^+$ line is optically thin in our study. From the abundance ratios of HNC, HCO$^+$, and HCN for each IRDC in Table 4, we find that HNC is more abundant than HCO$^+$ and HCN, except for IRDC G331.035-00.418, which agree with the fact that HNC molecule is the tracer of the cold gas. And the derived $N_{\text{HNC}}/N_{\text{HCN}} = 1.47 ± 0.50$ is consistent with the results in the dark cloud cores (Hirota et al. 1998). $N_{\text{HNC}}/N_{\text{HCO}^+}$ is approximately equal to 1, implying the similar origin and chemistry evolution of these two molecules. Furthermore, we also calculate the average abundance ratios ($N_{\text{HNC}}/N_{\text{HCN}}, N_{\text{HNC}}/N_{\text{HCO}^+}$, and $N_{\text{HNC}}/N_{\text{HCO}^+}$) of the 14 southern IRDCs, which are presented in Table 5. From Table 5, we find that $N_{\text{HNC}}/N_{\text{HCO}^+}$ is almost the same in the error scale in the three different environments, suggesting that the abundance ratio of HCN to HCO$^+$ may be not affected by the environments. The differences of other two ratios $N_{\text{HNC}}/N_{\text{HCN}}$ and $N_{\text{HNC}}/N_{\text{HCO}^+}$ indicate that IRDCs may represent the chemistry of earlier star formation.
4.3.3 The relationship between abundance ratios and distances

Figure 18 shows the relationships between the abundance ratios and the distances of the 14 southern IRDCs. $N_{\text{HCO}^+)/N_{\text{HNC}}$, $N_{\text{HCO}^+)/N_{\text{HNC}}$ and $N_{\text{HCN}}/N_{\text{HNC}}$ all show a linear relationship with the distances. The relationships are:

$$N_{\text{HCO}^+)/N_{\text{HNC}}} = (0.06 \pm 0.07) \times d + (0.66 \pm 0.21)$$

(9)

$$N_{\text{HCO}^+)/N_{\text{HNC}}} = (0.03 \pm 0.03) \times d + (0.47 \pm 0.07)$$

(10)

$$N_{\text{HCN}}/N_{\text{HNC}} = (0.03 \pm 0.08) \times d + (0.56 \pm 0.23)$$

(11)

From above relationships, we find the abundance ratios $O/N$ increasing slowly with the distances of the IRDCs, and a small increase is also found for the abundance ratio $N_{\text{HCN}}/N_{\text{HNC}}$ to the distance. Since the errors and limit data, the more studies should be done to check this conclusion.

5 SUMMARY

We do the research of 14 southern IRDCs with $N_{\text{H}^+}(1-0)$, HCN(1-0), HCO$^+$(1-0), and HCN(1-0) lines of the MALT90 survey and Spitzer 8 μm, 24 μm data. The integrated intensity diagrams of the four molecular lines are mapped and the physical parameters are obtained for the 14 southern IRDCs. We also discuss the kinetic processes and explore the chemical features. Our main results are summarized as follows.

1. The Spitzer images show that the 14 IRDCs are in different evolutionary stages, from "starless cores" with no IR emissions to "red cores" with the strong 8 μm emission.

2. According to the optically thick HNC and HCO$^+$ line profiles and mappings, three IRDCs (IRDC G331.035-00.418, G331.708+00.583, and G341.942-00.167) are found to have the infall motions, while other IRDCs without the star-forming activity may be in much earlier stage.

3. The integrated intensity of HNC, HCO$^+$ and HCN correlate well with each other for the 14 IRDCs, implying a close link to their chemistry evolution in the IRDCs.

4. The obtained physical parameters show that $T_{\text{ex}}$ is $< 25$ K for all the 14 IRDCs and $N_{\text{H}^+}$ line is optically thin in the IRDCs.

The column densities of the four molecules span up to two orders $10^{12} \sim 10^{13}$ and their corresponding abundances are in the range of $10^{-11}$ to $10^{-9}$. The average abundance ratios $N_{\text{HNC}}/N_{\text{HCO}^+} = 1.47 \pm 0.50$, $N_{\text{HNC}}/N_{\text{HCO}^+} = 1.47 \pm 0.22$ show significant difference with those of ISM and star forming regions, indicating that the environment of earlier star formation may be different. However, $N_{\text{HNC}}/N_{\text{HCO}^+} = 1.24 \pm 0.41$ is almost the same with that of the other environments, suggesting that the abundance ratio of HCN to HCO$^+$ may be not affected by the environment.

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Figure 1. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G003.309-00.399. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 µm and that in the right plane is Spitzer MIPSGAL 24 µm. The red dash line represents the $V_{LSR}$ of N$_2$H$^+$ line
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Figure 2. The spectra and the integrated intensity maps of $\text{N}_2\text{H}^+$, HNC, HCO$^+$, and HCN in IRDC G003.436-00.572. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 µm and that in the right plane is Spitzer MIPSGAL 24 µm. The red dash line represents the $V_{\text{LSR}}$ of $\text{N}_2\text{H}^+$ line.
Figure 3. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G010.402-00.202. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the V$_{LSR}$ of N$_2$H$^+$ line.
Figure 4. The spectra and the integrated intensity maps of $N_2H^+$, HNC, HCO$^+$, and HCN in IRDC G010.990-00.083. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the $V_{LSR}$ of $N_2H^+$ line.
Figure 5. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G308.121-00.152. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 µm and that in the right plane is Spitzer MIPSGAL 24 µm. The red dash line represents the V$_{LSR}$ of N$_2$H$^+$ line.
Figure 6. The spectra and the integrated intensity maps of $N_2H^+$, HNC, HCO$^+$, and HCN in IRDC G317.701+00.110. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 μm and that in the right plane is Spitzer MIPSGAL 24 μm. The red dash line represents the $V_{LSR}$ of $N_2H^+$.
Figure 7. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G321.756+00.029. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the V$_{LSR}$ of N$_2$H$^+$ line.
Figure 8. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G331.035-0.0418. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the $V_{LSR}$ of N$_2$H$^+$ line.
Figure 9. The spectra and the integrated intensity maps of $\text{N}_2\text{H}^+$, HNC, HCO$^+$, and HCN in IRDC G331.708+00.583. The spectra are in the left; the grayscale in the middle plane is *Spitzer IRAC* 8 $\mu$m and that in the right plane is *Spitzer MIPSGAL* 24 $\mu$m. The red dash line represents the V$_{LSR}$ of $\text{N}_2\text{H}^+$ line.
Figure 10. The spectra and the integrated intensity maps of $N_2H^+$, HNC, HCO$^+$, and HCN in IRDC G334.198-00.202. The spectra are in the left; the grayscale in the middle plane is *Spitzer IRAC 8 µm* and that in the right plane is *Spitzer MIPSGAL 24 µm*. The red dash line represents the $V_{LSR}$ of $N_2H^+$ line.
Figure 11. The spectra and the integrated intensity maps of N$_2$H$^+$, HNC, HCO$^+$, and HCN in IRDC G337.764+00.338. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 µm and that in the right plane is Spitzer MIPSGAL 24 µm. The red dash line represents the V$_{LSR}$ of N$_2$H$^+$ line.
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Figure 12. The spectra and the integrated intensity maps of $N_2H^+$, HNC, HCO$^+$, and HCN in IRDC G341.942-00.167. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the $V_{LSR}$ of $N_2H^+$ line.
Figure 13. The spectra and the integrated intensity maps of $\text{N}_2\text{H}^+$, HNC, HCO$^+$, and HCN in IRDC G344.726-00.541. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 $\mu$m and that in the right plane is Spitzer MIPSGAL 24 $\mu$m. The red dash line represents the $V_{\text{LSR}}$ of $\text{N}_2\text{H}^+$ line.

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Figure 14. The spectra and the integrated intensity maps of \( \text{N}_2\text{H}^+ \), HNC, \( \text{HCO}^+ \), and HCN in IRDC G345.556+00.026. The spectra are in the left; the grayscale in the middle plane is Spitzer IRAC 8 \( \mu \text{m} \) and that in the right plane is Spitzer MIPSGAL 24 \( \mu \text{m} \). The red dash line represents the VLSR of \( \text{N}_2\text{H}^+ \) line.
Figure 15. The upper plane: the HCO$^+$ map grid of IRDC G331.035-00.418 and the extracted spectra of N$_2$H$^+$ (black), HNC (green) and HCO$^+$ (blue) lines in two positions, corresponding to the red lines in the map grid. The black dash line and the red dash line mark the position of the $V_{\text{LSR}}$ of N$_2$H$^+$ line and the absorption dip of the optically thick lines; The bottom plane: the HCO$^+$ map grid of IRDC G341.942-00.167 and the extracted spectra of N$_2$H$^+$ (black), HNC (green) and HCO$^+$ (blue) lines in two positions, corresponding to the red lines in the map grid. The black dash line and the red dash line mark the position of the $V_{\text{LSR}}$ of N$_2$H$^+$ line and the absorption dip of the optically thick lines.
Figure 16. the HCO\(^+\) map grid of IRDC G331.708+00.583 and the extracted spectra of N\(_2\)H\(^+\) (black), HNC (green) and HCO\(^+\) (blue) lines in two positions, corresponding to the red lines in the map grid. The black dash line and the red dash line mark the position of the V\(_{LSR}\) of N\(_2\)H\(^+\) line and the absorption dip of the optically thick lines.

Figure 17. Left: plot averaged integrated intensity of HCO\(^+\) vs. those of HCN for the 14 IRDCs. Right: same for HNC vs. HCN. The red dash lines represent the linear fitting results.
Figure 18. Left: plot average abundance ratios of HCO$^+$ to HCN vs. the distances of the 14 IRDCs. Middle: plot average abundance ratios of HCO$^+$ to HNC vs. the distances of the 14 IRDCs. Right: plot average abundance ratios of HCN to HNC vs. the distances of the 14 IRDCs. The red dash lines represent the linear fitting results.