Chemical Evolution of N$_2$H$^+$ in Six Massive Star-forming Regions

Nai-Ping Yu©, Jin-Long Xu, Jun-Jie Wang, and Xiao-Lan Liu©
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China

Received 2018 June 6; revised 2018 August 13; accepted 2018 August 15; published 2018 October 1

Abstract

To investigate how the abundance of N$_2$H$^+$ varies as massive clumps evolve, here we present a multiwavelength study toward six molecular clouds. All of these clouds contain several massive clumps in different evolutionary stages of star formation. Using archival data of the Herschel infrared Galactic Plane Survey (Hi-GAL), we made H$_2$ column density and dust temperature maps of these regions by the spectral energy distribution method. We found that all of the six clouds show distinct dust temperature gradients, ranging from ~20 to ~30 K. This makes them good candidates to study chemical evolution of molecules (such as N$_2$H$^+$) in different evolutionary stages of star formation. Our molecular line data comes from the Millimeter Astronomy Legacy Team Survey at 90 GHz (MALT90). We made column density and then abundance maps of N$_2$H$^+$. We found that when the dust temperature is above 27 K, the abundance of N$_2$H$^+$ begins to decrease or reaches a plateau. We regard that this is because in the photodissociation regions around classical H II regions, N$_2$H$^+$ is heavily destroyed by free electrons. However, when the dust temperature is below 27 K, the abundance of N$_2$H$^+$ increases with the dust temperature. This seems to be inconsistent with previous chemical models made in low-mass star-forming regions. In order to investigate whether this inconsistency is caused by a different chemistry in high-mass star-forming clumps, higher angular resolution observations are necessary.

Key words: ISM: abundances – ISM: clouds – ISM: molecules – H II regions

1. Introduction

Massive stars (≥8 $M_{\odot}$) play an important role in the evolution of galaxies and molecular clouds. They release large amounts of energy into their surrounding interstellar medium (ISM) and have an immense impact on the subsequent star formation therein. They enrich heavy elements of the cosmic space in the form of supernova explosions. Massive stars are rare and used to form in dense molecular clouds at far distances from the solar system. This makes it hard for us to make a clear picture of the processes of massive star formation. In the past few decades, both in theories and observations, a lot of research has been done to understand the formation of massive stars (e.g., Zinnecker & Yorke 2007; Deharveng et al. 2010). Generally speaking, high-mass stars evolve through prestellar cores in starless cores to protostars in hot cores, and then to a hyper-compact H II region (HCH II) or ultra-compact H II region (UCH II) when substantial UV photons and ionized stellar winds rapidly ionize the surrounding hydrogen. The final stages are compact and classical H II regions. However, compared with low-mass stars, the formation of a high-mass star is still not well understood. It is regarded that the chemical properties of molecular clouds undergoing star formation should also be different due to the physical changes in different star formation processes (e.g., Sakai et al. 2008; Vasyunina et al. 2011; Sanhueza et al. 2012). Although many studies have been done to understand massive star formation, less is studied about their chemistry. What is the chemistry of massive star formations? Are they different from their low-mass counterparts? Can the chemical evolution in massive star-forming regions be used as a chemical clock? Recently, several studies have focused on this subject (e.g., Vasyunina et al. 2011; Hoq et al. 2013; Miettinen 2014; Yu & Wang 2015; Yu & Xu 2016).

Compared with CO species, N$_2$H$^+$ is more resistant to freeze-out onto grains, thus it is regarded as a good tracer of dense gas in the early stages of star formation (Bergin et al. 2001). CO would easily be depleted onto the dust grains when the dust temperature is below 20 K. Lee et al. (2004) combined a sequence of Bonnor–Ebert spheres and the inside-out collapse model to describe dynamics from the preprotostellar stage to later stages. They found that N$_2$H$^+$ is primarily formed through the gas-phase reaction H$^+_2$ + N$_2$ → N$_2$H$^+$ + H$_2$, and destroyed by CO molecules in the gas phase. So it should be expected that in the early stages of star formation, the abundance of N$_2$H$^+$ is relatively high as CO depletes in the gas phase. As the central protostar evolves, the gas gets warm and CO molecules begin to evaporate from the dust grains when the dust temperature is above 20 K (Tobin et al. 2013). CO could destroy N$_2$H$^+$ through the reaction N$_2$H$^+$ + CO → HCO$^+$ + N$_2$ (e.g., Jørgensen et al. 2004; Lee et al. 2004). According to the work of Vigren et al. (2012), N$_2$H$^+$ can also be destroyed by free electrons in H II regions: N$_2$H$^+$ + e$^-$ → N$_2$ + H or NH + N. Research has been done to check the chemical evolution of N$_2$H$^+$ in massive star-forming regions. Using the molecular line maps from year one of the MALT90 Survey, Hoq et al. (2013) found that the abundance of N$_2$H$^+$ increases as a function of the evolutionary stage. Sanhueza et al. (2012) also found that both the column density and the abundance of N$_2$H$^+$ increase as the clumps evolve from quiescent (starless candidates) to red stages (H II region candidates). These results are inconsistent with the predictions of the chemical models introduced above. As these authors analyze, several reasons may account this phenomena: (i) chemical models of low-mass star-forming regions (e.g., Bergin & Langer 1997; Lee et al. 2004) focused on single low-mass cores, which cannot be compared with a clump (hosting tens or hundreds of cores). The Mopra beam is 38″, this makes it impossible to resolve a single massive star-forming core. The Mopra telescope not only probes the warm core gas, but also the surrounding cold diffuse material; (ii) the chemistry of N$_2$H$^+$ in massive star-forming regions may be
really different from their low-mass counterparts; (iii) the formation and destruction rate of N$_2$H$^+$ might not be as accurate as is currently believed. We should also mention here that the initial conditions may be very different in different molecular clouds. For example, in the Galaxy, the $^{12}$C/$^{13}$C ratio ranges from $\sim$20 to $\sim$70, depending on the distance to the Galactic center (e.g., Savage et al. 2002). This might make their results not statistically significant. Here we present a multi-wavelength study toward six massive star-forming regions containing several clumps in different evolutionary stages of star formation, with the aim to make a more clear picture of the chemical evolution of N$_2$H$^+$ in massive star-forming regions. With only six molecular clouds, our work cannot be statistically significant, but given that the clumps in each cloud likely have similar initial conditions, we wish to use a different approach to found out whether our results will be consistent with those of previous works. We introduce our sources and data in Section 2, an analysis is given in Section 3, results and discussions are in Section 4, and finally we summarize in Section 5.

2. Source and Data

In the following we present our source introduction in Section 2.1, molecular data of MALT90 in Section 2.2, and far-infrared data from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) and the Herschel infrared Galactic Plane Survey (Hi-GAL) in Section 2.3.
2.1. Source Selection

The source sample of this paper involves two filamentary clouds identified by Li et al. (2016), two bubbles from Churchwell et al. (2006, 2007), and two dense clouds from Rathborne et al. (2016). Their basic information is shown in Table 1. We can see that each source involves at least four dense clumps from the catalog of Contreras et al. (2013). Guzmán et al. (2015) classified the clumps into quiescent, protostellar, H II region, and photodissociation region (PDR) stages according to the schematic time line of a massive star formation. All of the six sources involve at least two stages. The effective radius of most clumps are larger than 38″, which means they can be resolved by the Mopra telescope. For G351.776−0.527, CN148, and S36, previous studies have already indicated that they are candidates of massive star-forming regions (e.g., Dewangan et al. 2015; Klaassen et al. 2015; Torii et al. 2017). For the other three sources, all of them involve at least one clump with a mass >10^{3}M_{\odot}. Given a typical star formation efficiency of 10%-30% (Lada et al. 2010) and a cluster having a Salpeter-type initial stellar mass function (IMF), we could expect a 10^{3}M_{\odot} clump to form a star cluster with massive stars >20M_{\odot}. Therefore, our sources are candidates of massive star-forming regions. In the following analysis, it can be noted that all of the six molecular clouds have a distinct dust temperature gradient, ranging from ~20 to ~30 K. This makes them good candidates to study the chemical
evolution of N$_2$H$^+$ in different evolutionary stages of massive star formation. In Figures 1–6, we show the composed Spitzer images of our sources overlaid with the ATLASGAL 870 μm contours.

2.2. MALT90

We use archival molecular data from the MALT90 Survey. MALT90 is an international project with the aim to characterize physical and chemical properties of massive star formation in our Galaxy (e.g., Foster et al. 2011, 2013; Jackson et al. 2013). This project was carried out with the Mopra Spectrometer (MOPS) arrayed on the Mopra 22 m telescope, which is located near Coonabarabran in New South Wales, Australia. The full 8 GHz bandwidth of MOPS was split into 16 zoom bands of 138 MHz, providing a velocity resolution of 0.11 km s$^{-1}$ at frequencies near 90 GHz. The beam size of Mopra is 38'' at 86 GHz, with a beam efficiency between 0.49 at 86 GHz and 0.42 at 115 GHz (Ladd et al. 2005). The targets of this survey are selected from the ATLASGAL clumps found by Contreras et al. (2013). The size of the data cube is 4/6 × 4/6, with a step of 9''. We downloaded the data files from the MALT90 homepage. For each source, we combined all of the N$_2$H$^+$ data cubes into a new data cube using the software package of the Continuum and Line Analysis Single-dish Software (CLASS). The analysis of the other molecules (C$_2$H, HC$_3$N, H$_3$CO$^+$, and so on) will come in another paper. The combined images of the N$_2$H$^+$ integrated emissions are...
also shown in Figures 1–6. An example of the N$_2$H$^+$ (1−0) averaged spectrum is shown in Figure 7.

2.3. ATLASGAL and Hi-GAL

ATLASGAL is the first systematic survey of the inner Galactic plane in the submillimeter (Siringo et al. 2009; Contreras et al. 2013). It provides high angular resolution (∼19 arcsec) of cold dust emissions in the Galaxy. For a dust temperature of 20 K, ATLASGAL is sensitive to gas with H$_2$ column densities exceeding 10$^{22}$ cm$^{-2}$. The Hi-GAL data set is comprised of five continuum images of the Milky Way Galaxy using the PACS (70 and 160 μm) and SPIRE (250, 350 and 500 μm) instruments. The nominal angular resolutions range from 5$''$/2 to 35$''$/2 for 70 and 500 μm. The high-frequency components provide high angular resolution and are unaffected by large-scale background and foreground emissions, while the low-frequency components are used to maintain contaminations.

Compared to ATLASGAL, Hi-GAL is more sensitive to dust emissions from the low-density ISM. The two surveys provide us with a unique unbiased catalog of filament candidates in the Galaxy (e.g., André et al. 2010; Li et al. 2016).

3. Analysis

3.1. Dust Temperature and H$_2$ Column Density

We made H$_2$ column density and dust temperature maps of each region by the spectral energy distribution (SED) method.
described by Wang et al. (2015). Given that Hi-GAL is sensitive to low-density gas of about $10^{21}$ cm$^{-2}$, background and/or foreground contaminations cause a serious problem when analyzing the Hi-GAL data. Following the steps described by Wang et al. (2015), we first remove the background and foreground emissions. After removing the background and foreground emissions, we regridded the pixels onto the same scale of 13$\arcsec$, and convolved all of the images to a spatial resolution of 45$\arcsec$, which is the measured beamsize of the Hi-GAL observations at 500 $\mu$m (Traficante et al. 2011). For each pixel, we use equation

$$I_\nu = B_\nu(1 - e^{-\tau_\nu})$$

(1)
to model intensities at various wavelengths. The optical depth, $\tau_\nu$, could be estimated through

$$\tau_\nu = \mu H_2 n_{H_2} \kappa_\nu N_{H_2}/R_{gd}.$$  

(2)

We adopt a mean molecular weight per H$_2$ molecule of $\mu H_2 = 2.8$ to include the contributions from helium and other heavy elements. $n_{H_2}$ is the mass of a hydrogen atom. $N_{H_2}$ is the column density. $R_{gd}$ is the gas-to-dust mass ratio which is set to be 100. According to Ossenkopf & Henning (1994), dust opacity per unit dust mass ($\kappa_\nu$) could be expressed as

$$\kappa_\nu = 5.0 \left(\frac{\nu}{600 \text{ GHz}}\right)^\beta \text{ cm$^2$ g$^{-1}$},$$

(3)

where the value of the dust emissivity index $\beta$ is fixed to 1.75 in our fitting. The two free parameters ($N_{H_2}$ and $T_d$) for each pixel could be fitted finally. The final resulting dust temperature and column density maps, which have a spatial resolution of 45$\arcsec$ with a pixel size of 13$\arcsec$, are shown in Figure 8.

3.1.1. Column Density and Abundance of N$_2$H$^+$

To smooth the molecular data into a new beamsize of 45$\arcsec$ with a new step of 13$\arcsec$. Assuming local thermal equilibrium (LTE) conditions and a beam filling factor of 1, the column density of N$_2$H$^+$ in every pixel can thus be calculated through

$$N(\text{N}_2\text{H}^+) = \frac{8\pi c^3}{3h} \frac{Q_{\text{rot}}}{g_u A_{ul}} \frac{\exp(E_1/kT_{ex})}{1 - \exp(-h\nu/kT_{ex})} \int \tau d\nu, \quad (4)$$

where $c$ is the velocity of light in the vacuum, $\nu$ is the frequency of the transitions, $g_u$ is the statistical weight of the upper level, $A_{ul}$ is the Einstein coefficient, $E_1$ is the energy of the lower level, and $Q_{\text{rot}}$ is the partition function. For the excitation temperature of $T_{ex}$, here we assume that $T_{ex}$ is equal to the dust temperature derived above in each pixel. The value of $R$ is 5/9, taking into account the satellite lines corrected by their relative opacities (Sanhueza et al. 2012). We use approximation

$$\int \tau d\nu = \frac{\tau}{1 - \exp(-\tau)} \int T_{mb,d\nu} d\nu,$$  

(5)
to take $\tau_{N_2H^+}$ into account. N$_2$H$^+$ (1−0) has seven hyperfine components (e.g., Pagani et al. 2009; Keto & Rybicki 2010). As shown in the example in Figure 7, the seven hyperfine structures of N$_2$H$^+$ (1−0) blended into three groups because of the turbulent line widths. We estimate the optical depth of N$_2$H$^+$ (1−0) by the method described by Purcell et al. (2009).

The integrated intensities of Group 1/Group 2 should be in the ratio of 1:5, assuming that the line widths of the individual hyperfine components are all equal. The optical depth of N$_2$H$^+$ ($\tau_{N_2H^+}$) can then be derived using the equation

$$\frac{\int T_{mb,\text{Group1}} d\nu}{\int T_{mb,\text{Group2}} d\nu} = \frac{1 - \exp(-0.2\tau)}{1 - \exp(-\tau)}.$$  

(6)

By solving Equations (4) and (6) in each pixel where the Group 2 emission of N$_2$H$^+$ is greater than 6 $\sigma$, we got the column density maps of N(N$_2$H$^+$). For the uncertainties of column density, here we only consider the errors from optical depth and integrated intensities. The mean uncertainty is about 20%. The abundance value of N$_2$H$^+$ ($\chi(N_2H^+)$) for each pixel can be calculated through $\chi(N_2H^+) = N(N_2H^+)/N(H_2)$. The N$_2$H$^+$ abundance maps are shown in Figure 9.

4. Results and Discussions

4.1. G351.776−0.527

G351.776−0.527 is a filamentary cloud identified by Li et al. (2016). It is also known as infrared dark cloud (IRDC) G351.77−0.51 (Simon et al. 2006). In the top panel of Figure 1, dark absorption features against the Galactic mid-infrared background radiation field are obvious. According to Leurini et al. (2011), the kinematic distance of this cloud is about 1 kpc. IRAS 17233−3606 lies in the center of the filament, where the dust temperature is more than 30 K. Previous studies indicate active massive star formation in this Infrared Astronomical Satellite (IRAS) source (e.g., Caswell et al. 1980; Menten 1991; Leurini et al. 2009). Using high-resolution observations of the Very Large Array (VLA), Klaassen et al. (2015) found a large-scale outflow from IRAS 17233−3606. Some dense clumps have also been found on the northeast and southwest part of G351.776−0.527. The dust temperature there is relatively low, indicating earlier evolutionary stages. From the top left panel of Figure 9, we can see that the abundance of N$_2$H$^+$ is highest in the center and southeast side of IRAS 17233−3606. The top left panel of Figure 10 indicates that the abundance of N$_2$H$^+$ increases with the increment of the dust temperature in G351.776−0.527. This result is inconsistent with the chemical models of low-mass star formation.
4.2. G340.301−0.387

G340.301−0.387 is also a filamentary cloud identified by Li et al. (2016). From Figure 2, we can see that most of the dense gas is in the northwest part of this cloud, where the gas is also more evolved. The clumps in the southeast show no distinct Spitzer 8 μm emissions, indicating the gas here is less evolved. The dust temperature map shows a distinct temperature gradient, decreasing from ∼27 K in the northwest to ∼20 K in the southeast. The N$_2$H$^+$ abundance map shows a similar trend, also decreasing from northwest to southeast. The $T_d - \chi(N_2H^+)$ relation map in Figure 10 suggests a positive correlation. This trend is also inconsistent with chemical models of low-mass star formation, which suggests the abundance of N$_2$H$^+$ should decrease as star formation evolves.

4.3. CN148 and S36

CN148 and S36 are two infrared bubbles found by Churchwell et al. (2006, 2007). The arc-shaped distributions of N$_2$H$^+$ (1−0) emission, the 870 μm dust emission, and the polycyclic aromatic hydrocarbon features trace PDRs around the two bubbles. A multiwavelength study of CN148 carried out by Dewangan et al. (2015) suggests triggered star formation when the bubble expands into the surrounding ISM. A distinct dust temperature gradient can be noted around the two bubbles. The dust is quite hot (more than 30 K) on the PDRs, and decreases to ∼20 K outside of the PDRs. According to Guzmán et al. (2015), the clumps found by Contreras et al. (2013) in the two regions range from the quiescent to PDR stages. Our study shows the abundance of N$_2$H$^+$ is relatively low on the PDRs.
Figure 9. Calculated N$_2$H$^+$ abundance maps of the six sources. The pluses mark the dense clumps listed in Table 1. The black circles shown in each image indicates the beam size of 45″.
This is consistent with chemical models, as N$_2$H$^+$ is regarded to be destroyed by free electrons (e.g., Dislaire et al. 2012; Vigren et al. 2012). In a previous paper (Yu & Xu 2016), we also found that the abundance of N$_2$H$^+$ seems to decrease as a function of Lyman continuum fluxes (N$_L$) in compact H II regions, indicating that this molecule could be destroyed by UV photons when H II regions have formed. The $T_d - \chi$(N$_2$H$^+$) relation maps in Figure 10 suggest that the abundance of N$_2$H$^+$ increases when the dust temperature increases from $\sim$18 to $\sim$27 K, and drops when the dust temperature is more than 27 K. Again, the evolution trend of N$_2$H$^+$ is inconsistent with the chemical models when the dust temperature is below 27 K.
4.4. G326.432+0.916 and G326.641+0.612

These two sources are two dense clouds we selected from Rathborne et al. (2016). Even though they are not listed as bubbles by Churchwell et al. (2006, 2007), we can see distinct radio emissions from the Sydney University Molonglo Sky Survey (SUMSS; 843 MHz; Mauch et al. 2003), indicating that they are also two classical H II regions. The situations of these two sources are quite similar to CN148 and S36. The dust temperature in the two regions also decreases from PDR to the gas outside. The $T_d - \chi (N_2H^+)$ relation maps of the two sources also show a turning point near 27 K.

4.5. Discussions

In the chemical models of low-mass star formation (e.g., Bergin & Langer 1997; Lee et al. 2004), a relative enhancement of $N_2H^+$ abundance is expected in the cold prestellar phase, as CO is thought to be depleted in starless cores. As the central star evolves, the gas gets warm and CO should evaporate from the dust grains if the dust temperature exceeds about 20 K (Tobin et al. 2013). Thus we could expect the $N_2H^+$ abundance to decrease as a function of the dust temperature. In order to investigate the chemical evolution of $N_2H^+$ as clumps evolve, here we present a multiwavelength study toward six molecular clouds containing several clumps in different evolutionary stages of star formation. The initial conditions could be supposed to be the same in the same molecular cloud. Our study indicates that when the dust temperature is below 27 K, the abundance of $N_2H^+$ increases with the dust temperature. Previous studies (e.g., Sanhueza et al. 2012; Hoq et al. 2013; Miettinen 2014) also show this similar trend. The result of our study is consistent with those previous studies, although we used a different approach. As Hoq et al. (2013) suggest, chemical processes in massive star-forming regions may really differ from low-mass star formation. The mass infall rate, UV flux, and density in massive star formation regions are indeed different from their low-mass counterparts. The large beam of Mopra may also be the reason for this inconsistency. Chemical models of low-mass star-forming regions (e.g., Bergin & Langer 1997; Lee et al. 2004) focused on single low-mass cores, which cannot be compared with a clump. Higher angular resolution observations and chemical models should be carried out to study the chemical evolution of $N_2H^+$ in the early stages of massive star formation. In the PDRs where the dust temperature is more than 27 K, our study indicates that the abundance of $N_2H^+$ begins to decrease (CN148, S36, and G326.432+0.916) or reaches a plateau (G351.776–0.527 and G326.641+0.612). This is consistent with chemical models, as $N_2H^+$ is prone to be destroyed by free electrons (e.g., Vigen et al. 2012; Yu & Xu 2016). Figure 14 in Sanhueza et al. (2012) and Figure 5 in Hoq et al. (2013) indicate the increase of $N_2H^+$ abundance was up to the protostellar phase, and then for the red clumps or PDR clumps there was no significant increase or decrease. This phenomena is very similar to our sources of G351.776–0.527 and G326.641+0.612, where the $N_2H^+$ abundance reaches a plateau and becomes more or less constant when $T_d > 27$ K. Hoq et al. (2013) do not see the decrease from their protostellar to H II/PDR clumps, because most sources in their H II/PDR catalog consists of compact H II regions, which means the size of the ionized gas is no more than 0.1 pc. Given a typical distance of 3 kpc for a massive star-forming region, the Mopra telescope not only probes the ionized gas, but also the surrounding cold diffuse material. Large-scale infalls have also been found in many compact H II regions (e.g., Kato & Wood 2006; Yu et al. 2015). In our six sources, all of the PDRs are located around classical H II regions, where there is no large-scale infall and the ionized gas could be resolved by the Mopra telescope. This may be the reason that we see the decrease of $\chi (N_2H^+)$ when $T_d$ is above 27 K in CN148, S36, and G326.432+0.916.

5. Summary

We present a multiwavelength study toward six massive star-forming regions to investigate the chemical evolution of $N_2H^+$ as clumps evolve. Using archival data of Hi-GAL, we made $H_2$ column density and dust temperature maps of these regions through the SED method. We found that all of the six sources show distinct dust temperature gradients, ranging from $\sim$20 to $\sim$30 K. Previous infrared studies and the dust temperature images indicate that the physical and chemical properties are quite different in different parts of these sources. This makes them good candidates for us to study the chemical evolution of $N_2H^+$ in different evolutionary stages of massive star formation. Using the molecular line data of MALT90, we made the abundance maps of $N_2H^+$. We found that when the dust temperature is above 27 K, the abundance of $N_2H^+$ begins to decrease or reaches a plateau. We regard that this is because in the PDRs around classical H II regions, $N_2H^+$ is heavily destroyed by electrons. We also found that when the dust temperature is below 27 K, the abundance of $N_2H^+$ increases with the dust temperature. This is inconsistent with the chemical models of low-mass star formation. In order to investigate whether this inconsistency is caused by a different chemistry in high-mass star-forming clumps, higher angular resolution observations are necessary.

We are very grateful to the anonymous referee for comments and suggestions. This paper has made use of information from the ATLASGAL Database Server. The Red MSX Source survey was constructed with support from the Science and Technology Facilities Council of the UK. The ATLASGAL project is a collaboration between the Max-Planck-Gesellschaft, the European Southern Observatory (ESO), and the Universidad de Chile. This research made use of data products from the Millimetre Astronomy Legacy Team 90 GHz (MALT90) survey. The Mopra telescope is part of the Australia Telescope and is funded by the Commonwealth of Australia for operation as National Facility managed by CSIRO. This paper is supported by National Natural Science Foundation of China under grants of 11503037.

ORCID iDs

Nai-Ping Yu @ https://orcid.org/0000-0003-1241-7439
Xiao-Lan Liu @ https://orcid.org/0000-0002-1768-9591

References

André, P., Men’shchikov, A., Bontemps, S., et al. 2010, A&A, 518, L102
Bergin, E. A., Ciardi, D. R., Lada, C. J., Alves, J., & Lada, E. A. 2001, ApJ, 557, 209
Bergin, E. A., & Langer, W. D. 1997, ApJ, 486, 316

5 http://atlasgal.mpifr-bonn.mpg.de/cgi-bin/ATLASGAL_DATABASE.cgi
Caswell, J. L., Haynes, R. F., & Phys, J. 1980, IAUC, 3509, 2
Churchwell, E., Povich, M. S., Allen, D., et al. 2006, ApJ, 649, 759
Churchwell, E., Watson, D. F., Povich, M. S., et al. 2007, ApJ, 670, 428
Contreras, Y., Rathborne, J. M., Guzman, A., et al. 2017, MNRAS, 466, 340
Contreras, Y., Schuller, F., Urquhart, J. S., et al. 2013, A&A, 549, A45
Deharveng, L., Schuller, F., Anderson, L. D., et al. 2010, A&A, 523, 6
Dewangan, L. K., Ojha, D. K., Grave, J. M. C., & Mallick, K. K. 2015, MNRAS, 466, 2640
Dislaire, V., Hily-Blant, P., Faure, A., et al. 2012, A&A, 537, 20A
Foster, J. B., Jackson, J. M., Barnes, P. J., et al. 2011, ApJS, 197, 25
Foster, J. B., Rathborne, J. M., Sanhueza, P., et al. 2013, PASA, 30, 38
Guzmán, A., Sanhueza, P., Contreras, Y., et al. 2015, ApJ, 815, 130
Hoq, S., Jackson, J. M., Foster, J. B., et al. 2013, ApJ, 777, 157
Jackson, J. M., Rathborne, J. M., Foster, J. B., et al. 2013, PASA, 30, 57
Jørgensen, J. K., Schöier, F. L., & van Dishoeck, E. F. 2004, A&A, 416, 603
Keto, E., & Rybicki, G. 2010, ApJ, 716, 1315
Keto, E., & Wood, K. 2006, ApJ, 637, 850
Klaassen, P. D., Johnston, K. G., Leurini, S., & Zapata, L. A. 2015, A&A, 575, 54
Lada, C. J., Lombardi, M., & Alves, J. F. 2010, ApJ, 724, 687
Ladd, N., Purcell, C., Wong, T., & Robertson, S. 2005, PASA, 22, 62
Lee, J.-E., Bergin, E. A., & Evans, N. J., II 2004, ApJ, 617, 360
Leurini, S., Codella, C., Zapata, L. A., et al. 2009, A&A, 507, 1443
Leurini, S., Pillai, T., Stanke, T., et al. 2011, A&A, 533, 85
Li, G.-X., Urquhart, J. S., Leurini, S., et al. 2016, A&A, 591, A5
Mauch, T., Murphy, T., Buttery, H. J., et al. 2003, MNRAS, 342, 1117
Menten, K. M. 1991, ApJL, 380, L75
Miettinen, O. 2014, A&A, 562, A3
Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943
Pagani, L., Daniel, F., & Dubernet, M.-L. 2009, A&A, 494, 719
Purcell, C. R., Longmore, S. N., Burton, M. G., et al. 2009, MNRAS, 394, 323
Rathborne, J. M., Whitaker, J. S., Jackson, J. M., et al. 2016, PASA, 33, e030
Sakai, T., Sakai, N., Kamegai, K., et al. 2008, ApJ, 678, 1049
Sanhueza, P., Jackson, J. M., Foster, J. B., et al. 2012, ApJ, 756, 60
Savage, C., Apponi, A. J., Zmierski, L. M., & Wyckoff, S. 2002, ApJ, 578, 211
Simon, R., Jackson, J. M., Rathborne, J. M., & Chambers, E. T. 2006, ApJ, 639, 227
Siringo, G., Kreysa, E., Kovács, A., et al. 2009, A&A, 497, 945
Tobin, J. J., Bergin, E. A., Hartmann, L., et al. 2013, ApJ, 765, 18
Torii, K., Hattori, Y., Hasegawa, K., et al. 2017, ApJ, 840, 111
Traficante, A., Calzoletti, L., Veneziani, M., et al. 2011, MNRAS, 416, 2932
Vasyunina, T., Linz, H., Henning, Th., et al. 2011, A&A, 527, A88
Vigren, E., Zhaunerchyk, V., Hamberg, M., et al. 2012, ApJ, 757, 34
Wang, K., Testi, L., Ginsburg, A., et al. 2015, MNRAS, 450, 4043
Whitaker, J. S., Jackson, J. M., Rathborne, J. M., et al. 2017, ApJ, 154, 140
Yu, N. P., & Wang, J. J. 2015, MNRAS, 451, 2507
Yu, N. P., Wang, J. J., & Li, N. 2015, MNRAS, 451, 2507
Yu, N. P., & Xu, J. L. 2016, ApJ, 833, 248
Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481