Comparison of NH3 and 12CO, 13CO, C18O Molecular Lines in the Aquila Rift Cloud Complex (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

We present observations of the Aquila Rift cloud complex at 23.708 and 115.271 GHz conducted with the Nanshan 26 m radio telescope and the 13.7 m millimeter-wavelength telescope. We find that the CO(1−0) gas distribution is similar to the NH3 gas distribution throughout the Aquila Rift cloud complex. In several diffuse regions characterized by CO emission, we have identified dense clumps based on the distribution of detected ammonia molecular emission. Through comparison of spectral line parameters for NH3, 13CO, and C18O, our study reveals that the line center velocities of these three species are comparable and positively correlated, indicating that they originate from the same emission region. However, no significant correlation was identified for other parameters, including integrated intensity, line widths, main beam brightness temperature, and the column densities of NH3, 13CO, and C18O. The absolute difference in line-center velocities between the 13CO and NH3 lines is smaller than both the average line width of NH3 and that of 13CO, suggesting that there are no significant movements of NH3 clumps relative to their envelopes. The velocity deviation is likely due to turbulent activity within the clumps.

Key words: ISM: clouds – ISM: molecules – stars: formation

1. Introduction

The Aquila Rift cloud complex, a frequently studied and relatively nearby region, harbors a diverse collection of active star-forming regions, such as Serpens Main, Serpens South, Serpens MWC 297, and W 40 (Gutermuth et al. 2008). In this paper, we concentrate on the section of the Aquila Rift complex that contains two notable star-forming locations: Serpens South and W 40.

Serpens South, situated in the western portion of the Aquila Rift cloud complex, is a notable region of star formation that hosts a young embedded stellar cluster (Gutermuth et al. 2008). The region has a filamentary structure on the cusp of a burst of low-mass star formation. W 40 is a site of ongoing high-mass star formation located further to the east in equatorial coordinates. It not only contains dense molecular cores (Dobashi et al. 2005), but also includes a blistered H II region, which is powered by a pre–main-sequence star containing a compact OB association (e.g., Zeilik & Lada 1978; Smith et al. 1985; Vallee 1987; Kuhn et al. 2010; Rodríguez et al. 2010; Mallick et al. 2013).

The entire Aquila complex has been studied by the Herschel Gould Belt Survey, which provided detections of more than 500 starless cores imaged in dust emission at 70–500 m (Könyves et al. 2010). The recently measured distance to Serpens Main and W 40 is 436 pc, and the distance to Serpens South should be similar, since the two sources are connected kinematically (Ortiz-León et al. 2017, 2018). The mass of the W 40 giant molecular cloud was estimated to be 1.4×10^5 M by Su et al. (2020).

Comparative surveys of the CO(1−0) and NH3 molecular lines in star-forming regions have been presented by Levshakov et al. (2013), Li et al. (2016), Ladeyschikov et al. (2016), and Armillotta et al. (2020). Those studies show that both CO and 13CO are not only indicators of dense gas but also tracers of outflows and low-density regions (Levshakov et al. 2013). Furthermore, CO may exhibit saturation broadening. It is widely recognized that carbon-chain molecules are depleted from the gas phase in central regions due to freeze-out onto dust grains (e.g., Tafalla et al. 2004). Consequently, C-bearing molecules are typically found in the outer regions of cores. This is the reason that CO and 13CO are sub-optimal tracers for dense molecular gas. Conversely, nitrogen-bearing molecules like ammonia are concentrated within the inner cores, where the gas density reaches approximately 10^5 cm^{-3}. Ammonia remains detectable in the gas phase because it is resistant to depletion onto dust grains (e.g., Bergin & Langer 1997). Generally, the 12CO and 13CO emission lines are optically thick and thin, respectively, while the NH3 emission line can be both optically thick and optically thin. Therefore, these three lines share some common attributes while also exhibiting distinct characteristics.

Although a great number of molecular line observations have been carried out for the Aquila Rift cloud complex, such as in CO (Nakamura et al. 2017; Su et al. 2019, 2020; Komesh et al. 2020), in NH3 (Levshakov et al. 2013, 2014; Friesen et al. 2016; Tursun et al. 2020), and in H2CO (Komesh et al. 2019), there are no correlation studies between NH3 and CO molecules. In this paper, we selected the Aquila molecular cloud to carry out a correlation study between the NH3 and CO molecular lines.

The remainder of this paper is organized as follows: In Section 2 we describe our data and data reduction. Results are highlighted in Section 3, followed by the discussion presented in Section 4. Finally, conclusions are summarized in Section 5.

2.1. Archival Data

The data were taken between 2017 March and 2018 August with the Nanshan 26 m radio telescope (NSRT) located near Urumqi, P. R. China. We observed the NH3 (1,1) and (2,2) lines toward the Aquila Rift cloud complex using a 22.0–24.2 GHz dual polarization channel superheterodyne receiver. The main observation parameters of the Nanshan telescope and reference position are listed in Table 1.

The observations were centered on rest frequencies of 23.694 GHz for the (1,1) transition and 23.723 GHz for the (2,2) transition. The conversion of antenna temperatures T * to main beam brightness temperatures TMB was achieved using a beam efficiency value of 0.59. The system temperature, as measured on the T * scale, was approximately 50 K at a frequency of 23.708 GHz. The mapping was conducted using the on-the-fly (OTF) mode, utilizing a grid size of 6 and a sampling interval of 30 . Calibration of the observations was achieved by referencing periodically injected signals, occurring every 6 s, from a noise diode. IRAS 0033+636 (α = 00:36:47.51, δ = 63:29:02.1, J2000) was the subject of repeated observations (Schreyer et al. 1996), with a main beam brightness temperature TMB set at 4.5 K. The obtained systematic fluctuations and dispersion of brightness temperatures are minimal (see Appendix A of Tursun et al. 2020). The standard deviation of the mean is about 10% (see Figure A1 of Tursun et al. 2020). To validate the stability of our calibrations, we scrutinized our NH3 data alongside earlier NH3 data obtained with the Green Bank Telescope, as illustrated in Figure A2 of Tursun et al. (2020). The data sets acquired from G035.39−0.33 are in good agreement. All the observations were conducted under optimal weather conditions and at elevations higher than 20°.

The 12CO, 13CO, and C18O lines were simultaneously observed with the 13.7 m millimeter-wave telescope of the Purple Mountain Observatory in Delingha, and data were retrieved from the Millimeter Wave Radio Astronomy Database. The central coordinate of the OTF observation pattern is located at 18h30m03s, −2°02 40 (J2000). The half-power beamwidth (HPBW) of the observing system is approximately 50 . The observation system features a velocity resolution of 0.17 km s^{-1} and system temperature varying between 180 and 320 K. The 12CO, 13CO, and C18O data have been smoothed to the spatial resolution and cell size of the Nanshan 26 m radio telescope, which are 120 and 60 , respectively. The one-sigma noise levels for these data sets are 0.50 K, 0.35 K, and 0.35 K, respectively. The main observation parameters of the Delingha telescope are also listed in Table 1. Examples of the reduced and averaged spectral lines of NH3 (1,1), NH3 (2,2), 12CO, 13CO, and C18O are given in Figures 1 and 2.

2.2. Data Reduction

The CLASS and GREG packages of GILDAS were used for all data reduction. For NH3, we adopted two different fitting methods: the “GAUSS” fitting and the NH3 (1,1) fitting. To transform the widths of hyperfine blended lines into intrinsic line widths within the NH3 inversion spectrum (e.g., Barranco & Goodman 1998), we further processed the averaged spectra by employing the GILDAS software’s integrated “NH3 (1,1)” fitting technique, capable of simultaneously fitting all 18 hyperfine components. Through the NH3 (1,1) fitting, we can derive the integrated intensity TMB d , the line center velocity VLSR, the intrinsic line widths Δv for each hyperfine structure component, and the optical depth τ.

The main beam brightness temperatures (TMB) are derived using the GAUSS fitting method. These methods have been previously employed in similar studies, for instance by Wienen et al. (2012) and Wu et al. (2018). Figure 2 displays representative examples of the reduced and fitted spectra for the NH3 (1,1) and (2,2) inversion transitions. The spectral line parameters of the NH3 (1,1) transition lines are given in Table 2.

Owing to the relative weakness of the hyperfine satellite lines in the NH3 (2,2) transition, the optical depths for NH3 (2,2) were not measured. Instead, a single Gaussian profile was utilized to fit the main group of NH3 (2,2) hyperfine components. The spectral line parameters for the NH3 (2,2) transition lines are detailed in Table 2.

For 12CO, 13CO, and C18O, we applied the “GAUSS” fitting to obtain the integrated intensity, the velocity at line center, the line width, and the main beam brightness temperatures. The spectral line parameters for the CO isotopic lines are presented in Table 2.

3.1. The Distribution of the CO Gas

Figure 3 displays the integrated intensity maps for the 12CO, 13CO, and C18O lines, covering a velocity interval of $4 < \mathrm{VLSR} < 10$ km s^{-1}, and including only data with a signal-to-noise ratio (S/N) in excess of 3. The velocity range was selected with reference to the averaged spectral velocity range of the Aquila giant molecular cloud and the actual velocity of each spectral line. It is clear from Figure 3 that the 12CO molecule has the largest distribution range and was detected throughout the entire dense region. The 13CO molecule represents the diffuse gas and can also be found in the dense part, while the C18O molecule can only be identified within the most compact areas of Serpens South and W 40.

Examining the Aquila Rift morphology, it becomes evident that within the Serpens South area, there is a prominent ridge characterized by intense NH3 (1,1) emission stretching from southwest to northeast. This ridge encompasses numerous cores and extends over a total length of approximately 15 . NH3 emissions of lesser intensity are detected reaching further both to the south and to the north. The NH3 distribution exhibits a ring-shaped pattern, with its central point situated within region 4 (see Figure 1 in Tursun et al. 2020 for region 4). This feature, with a radius ranging from 25 to 30 , or around 3.5 pc, is approximately circular and shows significant emission of dust and NH3.

Figure 3 illustrates that the morphology of 12CO, 13CO, and C18O in the Aquila Rift is consistent with that of the Aquila giant molecular cloud discussed in Section 3.1 of Tursun et al. (2020), and is in a ring-like structure similar to the Herschel color infrared image.

3.2. Comparison of NH3 and CO Gas Distributions

The composite maps of the integrated intensity of the NH3 (1,1) and (2,2) lines with the 12CO, 13CO, and C18O molecular lines are shown in Figures 4 and 5, respectively. The color images present the integrated intensity distributions of the 12CO, 13CO, and C18O lines, and the contours indicate the integrated intensities of the NH3 (1,1) and (2,2) lines. The reference position is l = 28°.59, b = 3°.55. The integration range for the NH3 (1,1) and (2,2) lines is also $4 <$ VLSR < 10 km s^{-1}. Contours begin at a level of 0.13 K km s^{-1} (3σ) on the main beam brightness temperature scale, and increase in increments of 0.13 K km s^{-1} (see Figures 4, 5).

NH3 (1,1) exhibits an extended distribution and clearly traces the dense molecular gas, which includes Serpens South and W 40 (see Figure 4). NH3 (2,2) is only detected within the most compact areas of Serpens South and W 40, and exhibits a more limited distribution (see Figure 5). The maps show that the distribution of the NH3 gas is similar to the CO gas. In some CO molecular clouds, several dense clumps can be found using NH3 (1,1), as shown in the south and east regions in Figure 4.

The comparison of integrated intensities of NH3 (1,1) lines with the 12CO, 13CO, and C18O lines in the Aquila Rift cloud complex is shown in Figure 6. It shows that the integrated intensities of NH3 (1,1) lines were not significantly correlated with the integrated intensities of 13CO and C18O lines. Furthermore, the correlation between the integrated intensities of the NH3 (1,1) lines and the C18O lines is stronger than that between the NH3 (1,1) lines and the 12CO or 13CO lines (see Figures 4, 5 and 6).

3.3. Velocity Distributions of NH3 and CO Molecules

The right panel of Figure 7 shows the distributions of measured line center velocity for NH3 (1,1), 13CO, and C18O. The velocity range, peak value, average value, and standard deviation for the NH3, 13CO, and C18O lines are as follows: NH3: 4.53–9.69 km s^{-1}, peak value of 7.00 km s^{-1}, average value of 6.99 km s^{-1}, and standard deviation of 0.76 km s^{-1}; 13CO: 4.69–8.22 km s^{-1}, peak value of 7.00 km s^{-1}, average value of 6.94 km s^{-1}, and standard deviation of 0.73 km s^{-1}; C18O: 6.09–9.80 km s^{-1}, peak value of 7.00 km s^{-1}, average value of 7.42 km s^{-1}, and standard deviation of 1.47 km s^{-1}. While the peak velocity values of the NH3, 13CO, and C18O lines are identical, the average velocity values of NH3 and 13CO are nearly the same.

The line center velocities of NH3 (1,1) are plotted against those of the 13CO and C18O lines in the left panel of Figure 7. It can be found that the correlations in velocity between the NH3 (1,1)–13CO and NH3 (1,1)–C18O lines are significant, with linear correlation coefficients (r) of 0.51 and 0.49, respectively. The solid red and green lines provide the linear fits for NH3 (1,1)–13CO and NH3 (1,1)–C18O, respectively. The blue dashed line indicates the same central velocity for both the CO and NH3 lines. We mapped the Aquila Rift cloud complex in NH3, 12CO, 13CO, and C18O (Figures 3, 4 and 5). The mappings reveal a consistent distribution of NH3, 12CO, 13CO, and C18O on a scale of 12 pc. The velocity correlation diagram for the Aquila Rift cloud complex (Figure 7) also indicates that the line center velocities of these lines are comparable and positively correlated, suggesting that they originate from the same emission region.

3.4. Line Width Distributions of NH3 and CO Molecules

The right panel of Figure 8 presents the distribution of observed line widths for the NH3 (1,1) transition, as well as for the 13CO and C18O isotopologues. For the NH3, 13CO, and C18O lines, the respective parameters are as follows: NH3 has a line width range of 0.10–5.09 km s^{-1} with a peak value of 1.00 km s^{-1}, an average value of 1.42 km s^{-1}, and a standard deviation of 2.52 km s^{-1}; 13CO spans a line width range of 1.10–5.61 km s^{-1} with a peak value of 3.00 km s^{-1}, an average value of 3.24 km s^{-1}, and a standard deviation of 1.46 km s^{-1}; C18O is characterized by a line width range of 0.17–6.78 km s^{-1}, a peak value of 1.00 km s^{-1}, an average value of 1.37 km s^{-1}, and a standard deviation of 0.28 km s^{-1}. The peak values and average line widths of the NH3 and C18O lines are similar to each other, whereas the 13CO lines exhibit higher peak values and broader average line widths.

The left panel of Figure 8 displays a comparison of the line widths for NH3 (1,1) with those of 13CO and C18O. The plot reveals that there is no significant correlation between the line widths of NH3 and the line widths of 13CO and C18O.

3.5. Main Beam Brightness Temperature Distributions of NH3 and CO Molecules

The right panel of Figure 9 shows the distributions of measured main beam brightness temperature for NH3 (1,1), 13CO, and C18O. The parameters for the NH3, 13CO, and C18O lines are detailed below: For NH3, the TMB range extends from 0.01 to 1.72 K, peaking at 0.02 K, with an average of 0.25 K and a standard deviation of 0.04 K. 13CO exhibits a TMB range from 0.70 to 6.45 K, reaching a peak at 1.50 K, with an average of 1.79 K and a standard deviation of 1.08 K. C18O is identified by a TMB range of 0.25–2.86 K, a peak value of 0.50 K, an average of 0.91 K, and a standard deviation of 0.06 K.

A comparison of main beam brightness temperatures of NH3 (1,1) with 13CO and C18O lines is shown in the left panel of Figure 9. It is evident that there is no significant correlation between the main beam brightness temperatures of the NH3 (1,1) line and those of 13CO and C18O.

3.6. Comparison of NH3 and CO Column Densities

For this investigation, the characteristics of the molecular gas have been analyzed based on the condition that the entire molecular gas sample is in a state of local thermodynamic equilibrium (LTE). We postulate that the 12CO emission is characterized by optical thickness, and we further consider a beam-filling factor of unity. Given this, we can calculate the excitation temperature (T) as follows (Pineda et al. 2010; Kong et al. 2015; Lin et al. 2016):

$$T_{ex} = \frac{5.53}{\ln\left(1 + \frac{5.53}{T^{12}_{mb,CO} + 0.82}\right)}$$

where T_{mb,CO}^{12} represents the maximum main-beam temperature of the 12CO transition in units of K. The effective radiation temperature is defined by Ulich & Haas (1976), which is $T_R^* = \frac{T_{mb}}{\eta_{mb}}$, and the temperature of the cosmic microwave background radiation is T_{bg} = 2.7 K. The excitation temperature ranges from 3.9 to 13.0 K across the entire observed region.

Assuming that different isotopologues have the same T , the optical depths of 13CO (τ_{13}), C18O (τ_{18}), and the column densities of 13CO (N(13CO)) and C18O (N(C18O)) were estimated as follows (Lada et al. 1994; Kawamura et al. 1998; Lin et al. 2016):

$$\tau_{13} = -\ln\left[1 - \frac{T_{mb,13CO}}{5.29}\left\{\left[\exp\left(\frac{5.29}{T_{ex}}\right) - 1\right]^{-1} - 0.164\right\}^{-1}\right]$$

$$N(^{13}\mathrm{CO}) = 2.42 \times 10^{14} \frac{\tau_{13}}{1 - \exp(-\tau_{13})} \frac{T_{ex} + 0.88}{\exp(-5.29/T_{ex})} \int T_{mb,13CO} dV$$

$$N(\mathrm{C}^{18}\mathrm{O}) = 2.42 \times 10^{14} \frac{\tau_{18}}{1-\exp(-\tau_{18})} \frac{T_{ex}+0.88}{\exp(-5.27/T_{ex})} \int T_{mb,C^{18}O} dV$$

where $J_\nu(T) = \frac{h\nu/k}{\exp(h\nu/kT)-1}$, $J_\nu(T_{ex})$ and $J_\nu(T_{bg})$ are the effective radiation temperatures, and ΔV is the FWHM in km s^{-1}.

The optical depth of C18O calculated by the above formula is between 0.1 and 3.4, with an average of 0.4 ± 0.2. The optical depth of 13CO ranges from 0.2 to 4.7, with an average of 3.8 ± 0.1. The column density of C18O ranges from 1.2 × 10^{13} to 9.7 × 10^{15} cm^{-2}, with an average of 9.8 (\$±\$1.6) × 10^{14} cm^{-2}, while that of 13CO ranges from 9.4 × 10^{15} to 3.4 × 10^{16} cm^{-2} with an average of 2.1 (\$±\$1.3) × 10^{16} cm^{-2}. The determined ranges for the column densities of 13CO and C18O are in agreement with those reported by Komesh et al. (2020) for dense interstellar clouds in the Aquila region.

The column density of NH3 (1,1) was calculated from our NH3 observation data using the method described in Tursun et al. (2020). The results show that the column density of NH3 in the Aquila region varies from 0.2 × 10^{14} to 6.4 × 10^{15} cm^{-2}, with an average measured at 2.1 (\$±\$1.6) × 10^{15} cm^{-2}. The measured NH3 column densities for the Aquila region are in agreement with those reported for other Gould Belt star-forming regions (Friesen et al. 2017), and exhibit a range in para-NH3 column density (log N(para-NH3)) between 13.0 and 15.5. In Serpens South, the NH3 column density varies from 0.3 × 10^{14} to 6.4 × 10^{15} cm^{-2}, with an average of 2.6(\$±\$1.4) × 10^{15} cm^{-2}, whereas in W40 the NH3 column density ranges from 0.2 to 7.6 × 10^{14} cm^{-2}, with an average of 2.6 (\$±\$2.1) × 10^{14} cm^{-2}.

The column density of NH3 (1,1) was plotted against the 13CO and C18O lines in Figure 10. It shows that the column density of NH3 (1,1) is similar to that of C18O, which is about two orders of magnitude less than that of 13CO. No significant correlation could be found between the column density of NH3 and those of 13CO and C18O.

4. Discussion

We plot the absolute value of the difference between 13CO and C18O and the NH3 line-center velocities from Gaussian fits in Figures 11(a) and (b). The average discrepancy between the central velocities of 13CO and NH3 is 0.04 ± 0.43 km s^{-1}, whereas the average velocity difference between C18O and NH3 is 0.24 ± 0.30 km s^{-1}. The variations in line-center velocities of 13CO and NH3 can be compared to the sound speed, which is 0.23 km s^{-1} (for the calculation of the sound speed see Section 4.3 of Tursun et al. 2020). The majority of clumps exhibit velocity differences that exceed the sound speed, with 28% displaying subsonic motion.

Figures 11(c) and (d) present the variations in line width discrepancies between the 13CO and C18O lines relative to NH3. The average value of the intrinsic line width difference is 1.80 ± 0.91 km s^{-1} between 13CO and NH3, and 0.07 ± 0.67 km s^{-1} between C18O and NH3.

The absolute value of the discrepancy between the 13CO and NH3 (1,1) line-center velocities is illustrated in Figure 12 as a function of the NH3 (1,1) line width. If there are significant movements of NH3 clumps relative to their envelopes, the differences in line-center velocities should be on the order of the 13CO line widths (Walsh et al. 2004). In Figure 12, the dashed red line, positioned at 1.42 km s^{-1}, denotes the average line width of NH3 (1,1), while the solid green line at 3.24 km s^{-1} represents the average 13CO line width. The dashed black line in the figure shows the rms of the absolute value of the velocity difference between 13CO and NH3 (1,1).

All points are below both the average line width of NH3 and the average line width of 13CO, indicating that there are not significant movements of NH3 clumps relative to their envelopes (as introduced previously, Walsh et al. 2004). The velocity variations are presumably due to turbulent activity within the clumps. Consequently, the small relative velocities between the NH3 clumps and the 13CO clouds impose stringent constraints on the role of turbulence in the formation of these clumps.

5. Summary

We present observations from the Nanshan 26 m telescope and the Delingha 13.7 m millimeter-wavelength telescope toward the Aquila Rift cloud complex. The distributions of NH3, 12CO, 13CO, and C18O were compared, and their spectral line parameters and derived physical parameters were analyzed. The main results are summarized as follows:

1. The CO gas distribution is similar to the NH3 gas distribution in the Aquila Rift cloud complex.
2. In some diffuse regions characterized by CO, we found several dense clumps according to the distribution of detected ammonia molecular emission.
3. We compared the integrated intensity, line center velocity, line width, main beam brightness temperature, and column density of NH3, 13CO, and C18O. Our results show that the line center velocities of the three species are comparable and positively correlated, which demonstrates that they originate from the same emission regions. No significant correlation was found for other parameters between NH3 and the 13CO and C18O lines.
4. The absolute difference in line-center velocities between the 13CO and NH3 lines is smaller than the average line width of NH3 and the average line width of 13CO. This suggests that there is no significant movement of NH3 clumps relative to their envelopes. The velocity deviation should come from turbulent activity in the clumps.

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