Observations of Ammonia in External Galaxies. II. Maffei 2

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Abstract

The ammonia \((J,K) = (1,1), (2,2), (3,3), \) and \((4,4)\) transitions at 23.7 – 24.1 GHz region were searched for in a nearby galaxy Maffei 2 to study relation between molecular abundances and physical conditions in galaxies. The \((1,1), (2,2), \) and \((3,3)\) emission lines were clearly detected. The rotational temperatures and ortho-to-para abundance ratios obtained are about 30 K and about 2.6, respectively. The abundance of \(\text{NH}_3\) relative to \(\text{H}_2\) in Maffei 2 was found to be the largest among galaxies where \(\text{NH}_3\) is already detected, and the abundance in Maffei 2 is more than an order of magnitude larger than the already reported upper limit in M82. Hence, we further confirmed the systematically peculiar molecular abundance in the aspect of formation mechanisms of molecules already reported in M82.

Key words: atomic and molecular processes — galaxies: abundances — galaxies: individual (Maffei 2) — galaxies: starburst — interstellar: molecules

1. Introduction

About 120 molecules have been detected in interstellar space and circumstellar envelopes of late-type stars. One fifth of them, 24 molecules, have already been detected in external galaxies (e.g. Henkel et al. 1991). Further detections of molecules in galaxies, and subsequently, studies of relation between the molecular abundances and the physical conditions are important to understand chemical processes in galaxies. Such knowledge is a basis to understand physics and evolution of galaxies by observations of molecular lines.

In particular, molecular abundances of two well-known starburst galaxies, NGC 253 and M82, have been extensively studied (e.g. Henkel, Mauersberger 1992). They have very rich and similar amount of molecular gas \((\text{H}_2\) column density \(\sim 10^{23} \text{ cm}^{-2}\)), and their distances from our Galaxy are nearly the same (about 3 Mpc). Consequently, they are good sources to compare the molecular abundances each other. As a result, clear difference in the molecular abundances has been found. Six molecules, SO, SiO, \(\text{NH}_3\), HNCO, \(\text{CH}_3\text{OH}\), and \(\text{CH}_3\text{CN}\), have been clearly detected in NGC 253, but not detected with comparable sensitivity in M82 (Henkel et al. 1987; Mauersberger et al. 1991; Mauersberger, Henkel 1991; Nguyen-Q-Rieu et al. 1991; Takano et al. 1995; Takano et al. 2000). Actually the abundances of these six molecules are significantly higher in NGC 253 than those (upper limits) in M82. We noticed that these six molecules have common characteristics on their formation mechanisms; their formations are related to grain and they are evaporated (or sputtered) from grain to gas phase, and/or they are efficiently produced in gas-phase in active regions such as shock regions and high-temperature regions (Takano et al. 1995, 2000). Furthermore, at least half of above six molecules, \(\text{NH}_3\), HNCO, and \(\text{CH}_3\text{OH}\), is more abundant not only in NGC 253 but in nearby galaxies with rich molecular gas than in M82. Based on these results, we concluded that molecular abundance in M82 is systematically peculiar in the aspect of formation mechanisms of molecules (Takano et al. 2000).
NH$_3$ is already detected in NGC 253 and IC 342 in external galaxies (Martin, Ho 1979; Takano et al. 2000). Further detections of NH$_3$ in external galaxies will contribute to the confirmation of the peculiarity in M82. In addition, NH$_3$ is a good probe to obtain important physical parameters such as temperature and ortho-to-para ratio, because lines with different excitations and different spin statistical species can be simultaneously observed around 23 GHz region.

In our preliminary survey of NH$_3$ in nearby galaxies, we detected possible features in a galaxy Maffei 2 with the Effelsberg 100-m radiotelescope in October 1998. Maffei 2 is a nearby (∼ 5 Mpc, Allen, Raimond 1972; Spinrad et al. 1973) barred galaxy [SBb(s) pec, Hurt et al. 1993a] obscured by our Galactic disk (b ∼ −0°.3). It has strong CO emissions (e.g. Weliachew et al. 1988), and detections of HNCO and CH$_3$OH among above six molecules have already been reported (Nguyen-Q-Rieu et al. 1991; Hüttemeister et al. 1997). We, therefore, searched for NH$_3$ deeply in Maffei 2, and detections are reported in this letter.

2. Observations

The observations were made with the NRO 45-m radiotelescope in 2000 June 1 to 9. The adopted central position is α(1950) = 02h38m07s98 and δ(1950) = 59°23'.24′.8. This is a peak of K-band image (H. Spinrad, private communication). The systemic velocity (LSR) is ∼ –10 km s$^{-1}$. Four inversion transitions of NH$_3$, (1,1), (2,2), (3,3), and (4,4) at 23693.495, 23722.633, 23870.129, and 24139.417 MHz, respectively, were observed simultaneously using a dual polarization HEMT amplifier receiver. Both circular polarizations were observed simultaneously. The system noise temperature was 150 – 260 K (single side band) depending on elevation and weather. The main beam efficiency ($\eta_{mb}$) was 0.82, and the beam size was 70″ (FWHM), which corresponds to about 1.7 kpc at the distance of 5 Mpc.

The backend used was eight acousto-optical spectrometers. The band width is 40 MHz, and the resolution is 37 kHz for each spectrometer. The frequency resolution corresponds to 0.47 km s$^{-1}$ at 23.7 GHz. The observations were made in a position switching mode. The off position was (∆α, ∆δ) = (0′.5, −12′), which is free from foreground Galactic lines (Rickard et al. 1977). The pointing was checked every ∼ 4 hours by observing an SiO maser line ($J = 1 – 0$, $v = 1$) from a nearby evolved star S Per; average of each pointing deviation was 7″. The calibration of the line intensity was made using the chopper-wheel method.

3. Results and Analysis

Figure 1 shows the obtained spectra. The (1,1), (2,2), and (3,3) emission lines of NH$_3$ were clearly detected, but the (4,4) line is only marginally detected at the $V_{LSR}$ ∼ 15 km s$^{-1}$. The lineshapes of the (1,1), (2,2), and (3,3) lines are similar each other and show double peaks at the $V_{LSR}$ of about −90 and 10 km s$^{-1}$. The intensities of the (1,1) and (3,3) lines are similar, but the intensity of the (2,2) line is about half of them. The line parameters are listed in table 1 for the total velocity range and for each velocity component ($V_{LSR} = -150 – -50$ km s$^{-1}$ and $-50 – 100$ km s$^{-1}$).

The analysis of the spectra was done with the similar method as in the case of NH$_3$ in NGC 253 (Takano et al. 2000). The rotational temperature from the (1,1) and (2,2) lines, and the ortho-to-para ratio from the (1,1), (2,2), and (3,3) lines are obtained by analyzing the line integrated intensity with the rotation diagram method (e.g. Turner 1991). The beam filling factor was estimated to be 0.039, where the distribution of NH$_3$ was assumed to be the same as CO. The size of the CO distribution employed was 30″ × 7′ (FWHM) from the observations of Ishiguro et al. (1989) and Hurt et al. (1993b). The estimated value of the filling factor affects evaluation of column densities, but not for rotational temperatures and ortho-to-para ratios. The rotation diagram is shown in figure 2. The obtained rotational temperatures are about 30 K for the total velocity range and for the two velocity components. The column densities are $1.5 \times 10^{15}$ cm$^{-2}$, $5.0 \times 10^{14}$ cm$^{-2}$, and $1.1 \times 10^{15}$ cm$^{-2}$ for the total velocity range, $-150 – -50$ km s$^{-1}$, and $-50 – 100$ km s$^{-1}$, respectively. In addition the column density ratios of ortho- and para-NH$_3$ ([ortho]/[para], hereafter “ortho-to-para abundance ratio”) are calculated to be $2.6^{+0.8}_{-1.3}$, $2.6^{+1.8}_{-2.3}$, and $2.6^{+1.4}_{-0.9}$ for above velocity ranges, respectively. The errors correspond to ∼3σ. These values are significantly larger than the value of high temperature limit of 1.0 (see section 4.2.). The obtained parameters are listed in table 2.

4. Discussion

4.1. The Abundances of NH$_3$ in the Galaxies

The abundance of NH$_3$ in Maffei 2 relative to H$_2$ ([NH$_3$]/[H$_2$]) is calculated from their column densities. As the column density of H$_2$, we employed $1.4 \times 10^{22}$ cm$^{-2}$ (Hüttemeister et al. 1995). The obtained abundance is $1 \times 10^{-7}$, which is higher than the corresponding values of $2.7 \times 10^{-8}$ in NGC 253 and $1.9 \times 10^{-8}$ in IC 342 (Takano et al. 2000). Maffei 2 has the highest abundance of NH$_3$ among galaxies where NH$_3$ is detected.

Abundances of NH$_3$ in our Galactic sources strongly depend on regions. The abundances are between $1 \times 10^{-8}$ and $10^{-4}$ as follows. In our Galactic center Sgr B2 the
abundances are reported to be \((1 - 10) \times 10^{-8}\) (Irvine et al. 1987) and \(8 \times 10^{-8} - 10^{-4}\) (Hüttemeister et al. 1993). In the cyanopolyne peak of TMC-1, which is a quiescent young dark cloud where ammonia formation is not yet prominent, the abundance is \(2 \times 10^{-8}\) (Irvine et al. 1987). In star forming regions abundances are typically more than \(10^{-7}\). For example the abundance in the Orion ridge is \(2 \times 10^{-7}\) (Irvine et al. 1987). The abundance in Maffei 2 is similar to this value.

The abundance in Maffei 2 is much higher than the upper limit of \(1.4 \times 10^{-9}\) in M82 (at \(T_{\text{rot}} = 30\) K, Takano et al. 2000), though star formation activity and amount of molecular gas of Maffei 2 are significantly lower than those in M82; peculiarity of the molecular abundance in M82 is further supported by the present result.

\section{4.2. Ortho-to-para Abundance Ratios of NH\textsubscript{3}}

There are ortho-NH\textsubscript{3} \((K = 3n, n \text{ is integer})\) and para-NH\textsubscript{3} \((K \neq 3n)\) due to the three equivalent hydrogen nuclei with spin 1/2. No dipole and collisional transitions are allowed between the ortho and para states. The spin statistical weight is 4 : 2 for ortho : para (e.g. Townes, Schawlow 1975). On the other hand, the number of the para levels is almost two times larger than that of the ortho levels, and consequently the ortho-to-para abundance ratio approaches to 1.0, if NH\textsubscript{3} is produced and equilibrated under high-temperature conditions \((\geq 40\) K). On the other hand, the ratio becomes quite large if NH\textsubscript{3} is produced and equilibrated under low-temperature conditions (e.g. more than 10 at 5 K), because the lowest level, \((0,0)\), belongs to ortho. The dependence of ortho-to-para abundance ratios of NH\textsubscript{3} on temperatures, which determine the distribution between ortho and para, was calculated and shown in figure 3 of Takano et al. (2000).

The ortho-to-para abundance ratios obtained in Maffei 2 are about 2.6 for all velocity components. The ratio at the total velocity component is \(2.6^{+1.1}_{-0.8}\) which corresponds to a temperature of distribution between ortho- and para-NH\textsubscript{3} of \(13^{+5}_{-3}\) K. If this temperature can be interpreted as a formation temperature of NH\textsubscript{3}, it was produced on low-temperature grain and subsequently evaporated to gas-phase.

Studies of NH\textsubscript{3} abundance in the aspect of an ortho-to-para abundance ratio have been limited. In our Galaxy, Unemoto et al. (1999) recently obtained ratios of \(1.3 - 1.7\), which are significantly higher than the value of high-temperature limit of 1.0, in the outflow lobe of a star forming region L1157. In external galaxies, ratios have been obtained only in NGC 253 (Takano et al. 2000). The values are quite different depending on the velocity components; \(~ 1\) for the relatively red-shifted component and more than \(~ 14\) for the relatively blue-shifted component. The ratio obtained in Maffei 2 is not so large as obtained in the relatively red-shifted component in NGC 253.

\section{4.3. Double Peak Spectra of NH\textsubscript{3}}

As shown in figure 1, the lineshapes of the NH\textsubscript{3} lines in Maffei 2 show double peak. Such double peak has already been reported at the CO \(J = 1 - 0\) (Sargent et al. 1985; Weliachew et al. 1988), \(J = 2 - 1\) (Sargent et al. 1985), and \(J = 3 - 2\) (Hurt et al. 1993b; Mauersberger et al. 1999) transitions. In addition, the H\textsubscript{2}CO \(2_{11} - 1_{10}\) and \(2_{12} - 1_{11}\) transitions (Hüttemeister et al. 1997), and HNC \(J = 1 - 0\) (Hüttemeister et al. 1995) transition also show the double peak. Ishiguro et al. (1989) found a molecular ring with a diameter of about 500 pc \(\times 240\) pc in the bar. Gas is deficient inside of the ring. These double peaks can be interpreted to originate from this ring structure. For CO and NH\textsubscript{3}, the velocity component at \(~ 10\) km s\(^{-1}\) is clearly stronger than that at \(~ 90\) km s\(^{-1}\). This may be related to the small scale asymmetries in the molecular bar (Ishiguro et al. 1989) and to the large scale asymmetry of the arms found by the infrared observation (Hurt et al. 1993a).

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\section{References}

Allen R.J., Rainmond E. 1972, A&A 19, 317
Henkel C., Baan W.A., Mauersberger R. 1991, A&AR 3, 47
Henkel C., Jacq T., Mauersberger R., Menten K.M., Steppe H. 1987, A&A 188, L1
Henkel C., Mauersberger R. 1992, Astrochemistry of Cosmic Phenomena, ed P.D. Singh (Kluwer Academic Publishers, Dordrecht) p111
Hurt R.L., Merrill K.M., Gatley I., Turner J.L. 1993a, AJ 105, 121
Hurt R.L., Turner J.L., Ho P.T.P., Martin R.N. 1993b, ApJ 404, 602
Hüttemeister S., Henkel C., Mauersberger R., Brouillet N., Wildling T., Millar T.J. 1995, A&A 295, 571
Hüttemeister S., Mauersberger R., Henkel C. 1997, A&A 326, 59
Hüttemeister S., Wilson T.L., Henkel C., Mauersberger R. 1993, A&A 276, 445
Irvine W.M., Goldsmith P.F., Hjalmarson Å. 1987, Interstellar Processes, ed D.J. Hollenbach, H.A. Thronson, Jr. (D. Reidel Publishing Company, Dordrecht) p561
Ishiguro M., Kawabe R., Morita K.-I., Okumura S.K., Chikada Y., Kasuga T., Kanzawa T., Iwashita H. et al. 1989, ApJ 344, 763
Martin R.N., Ho P.T.P. 1979, A&A 74, L7
Mauersberger R., Henkel C. 1991, A&A 245, 457
Mauersberger R., Henkel C., Walmsley C.M., Sage L.J., Wilk- 
lind T. 1991, A&A 247, 307
Mauersberger R., Henkel C., Walsh W., Schulz A. 1999, A&A  
341, 256
Nguyen-Q-Rieu, Henkel C., Jackson J.M., Mauersberger R.  
1991, A&A 241, L33
Rickard L.J., Turner B.E., Palmer P. 1977, ApJ 218, L51
Sargent A.I., Sutton E.C., Masson C.R., Lo K.Y., Phillips  
T.G. 1985, ApJ 289, 150
Spinrad H., Bahcall J., Becklin E.E., Gunn J.E., Kristian J.,  
Neugebauer G., Sargent W.L.W., Smith H. 1973, ApJ 180,  
351
Takano S., Nakai N., Kawaguchi K. 1995, PASJ 47, 801
Takano S., Nakai N., Kawaguchi K. 2000, submitted to PASJ
Townes C.H., Schawlow A.L. 1975, Microwave Spectroscopy  
(Dover, New York), p 72
Turner B.E. 1991, ApJS 76, 617
Umemoto T., Mikami H., Yamamoto S., Hirano N. 1999, ApJ  
525, L105
Weliachew L., Casoli F., Combes F. 1988, A&A 199, 29
Table 1. Observed line parameters of the ammonia (1,1), (2,2), (3,3), and (4,4) transitions.

| Transition | Velocity range (km s\(^{-1}\)) | \(\int T_{mb} dv\) \(^a\) (K km s\(^{-1}\)) | \(T_{mb}\) \(^b\) (mK) | \(V_{LSR}\) \(^b\) (km s\(^{-1}\)) | \(\Delta v\) (FWHP) \(^b\) (km s\(^{-1}\)) | Rms noise \((T_{mb})\) \(^c\) (mK) |
|------------|----------------------------------|---------------------------------|----------------|-----------------|----------------|----------------|
| (1,1)      | -150 – 100 (total)               | 0.89±0.06                       | 7.4            | ...             | ...            | 1.1            |
|            | -150 – -50                       | 0.29±0.04                       | 4.5            | -83             | 76             |                |
|            | -50 – 100                        | 0.59±0.04                       | 7.4            | 13              | 65             |                |
| (2,2)      | -150 – 100 (total)               | 0.50±0.04                       | 4.9            | ...             | ...            | 0.9            |
|            | -150 – -50                       | 0.16±0.03                       | 2.2            | -100            | 81             |                |
|            | -50 – 100                        | 0.34±0.03                       | 4.9            | 5               | 62             |                |
| (3,3)      | -150 – 100 (total)               | 0.95±0.04                       | 6.5            | ...             | ...            | 0.9            |
|            | -150 – -50                       | 0.29±0.03                       | 4.7            | -86             | 56             |                |
|            | -50 – 100                        | 0.66±0.03                       | 6.5            | 8               | 98             |                |
| (4,4)      | -50 – 100                        | 0.06±0.05\(^d\)                | 3.3            | 15              | ...            | 1.2            |

\(^a\) \(T_{mb} \equiv T_A/\eta_{mb}\) (\(\eta_{mb} = 0.82\)). The error corresponds to \(\sim 1\sigma\).
\(^b\) Obtained by Gaussian fit except for the (4,4) line.
\(^c\) Velocity resolution is 10 km s\(^{-1}\).
\(^d\) Only marginally detected.

Table 2. Ammonia rotational temperatures, column densities, ortho-to-para abundance ratios, and abundances.

| Velocity Component | \(T_{rot}\) \(^a\) (K) | Ortho (cm\(^{-2}\)) | Para (cm\(^{-2}\)) | Total (cm\(^{-2}\)) | Ortho-to-para \(^c\) | Abundance \(^d\) |
|-------------------|----------------|----------------|-----------------|--------------------|-------------------|----------------|
| -150 – 100 (total)| \(30^{+5}_{-2}\) | \((1.1\pm0.3) \times 10^{15}\) | \((4.3\pm0.4) \times 10^{14}\) | \((1.5\pm0.3) \times 10^{15}\) | \(2.6^{+1.1}_{-0.8}\) | \(1 \times 10^{-7}\) |
| -150 – -50 .......| \(30^{+5}_{-4}\) | \((3.6\pm2.0) \times 10^{14}\) | \((1.4\pm0.3) \times 10^{14}\) | \((5.0\pm2.0) \times 10^{14}\) | \(2.6^{+2.8}_{-1.3}\) | \(\ldots\) |
| -50 – 100 ....... | \(31^{+3}_{-2}\) | \((7.6\pm2.3) \times 10^{14}\) | \((2.9\pm0.3) \times 10^{14}\) | \((1.1\pm0.2) \times 10^{15}\) | \(2.6^{+1.4}_{-0.9}\) | \(\ldots\) |

\(^a\) Obtained from the populations between the (1,1) and (2,2) levels. The error corresponds to \(\sim 1\sigma\).
\(^b\) The error corresponds to \(\sim 1\sigma\).
\(^c\) The error corresponds to \(\sim 3\sigma\).
\(^d\) The column density of H\(_2\) (1.4 \times 10^{22}\) cm\(^{-2}\)) is taken from H"{u}ttemeister et al. (1995).
Fig. 1. Spectra in the frequency regions of the NH$_3$ (1,1), (2,2), (3,3), and (4,4) transitions from bottom to top. The LSR velocity shown is for each transition. The velocity resolution is 10 km s$^{-1}$. The lines show double peak structure. The (4,4) transition is only marginally detected.

Fig. 2. Rotation diagrams of the NH$_3$ lines. The points •, ◦, and ○ indicate the data points of integrated intensity which covers the total velocity range (−150 − 100 km s$^{-1}$), −150 − −50 km s$^{-1}$, and −50 − 100 km s$^{-1}$, respectively. Lines connecting the (1,1) and (2,2) data points are shown.
Figure 1: Takano, Nakai, Kawaguchi, Takano

Ammonia in Maffei 2

LSR Velocity / km s\(^{-1}\)

\(T_{\text{A}*} / \text{K}\)

(4,4)

(3,3)

(2,2)

(1,1)
Figure 2: Takano, Nakai, Kawaguchi, Takano

Rotational Temperatures
~30 K

log_{10} \left( \frac{\text{3kW}}{8n^{3}v_{r}^{2}S_{0}} \right) / \text{cm}^{2}

Maffei 2 Ammonia