THE ORTHO-TO-PARA RATIO OF AMMONIA IN THE L1157 OUTFLOW

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ABSTRACT

We have measured the ortho-to-para ratio of ammonia in the blueshifted gas of the L1157 outflow by observing the six metastable inversion lines from \((J, K) = (1, 1)\) to \((6, 6)\). The highly excited \((5, 5)\) and \((6, 6)\) lines were first detected in the low-mass star-forming regions. The rotational temperature derived from the ratio of four transition lines from \((3, 3)\) to \((6, 6)\) is \(130\pm140\) K, suggesting that the blueshifted gas is heated by a factor of \(10\) as compared to the quiescent gas. The ortho-to-para ratio of the \(\text{NH}_3\) molecules in the blueshifted gas is estimated to be \(1.3\pm1.7\), which is higher than the statistical equilibrium value. This ratio provides us with evidence that the \(\text{NH}_3\) molecules have been evaporated from dust grains with the formation temperature between 18 and 25 K. It is most likely that the \(\text{NH}_3\) molecules on dust grains have been released into the gas phase through the passage of strong shock waves produced by the outflow. Such a scenario is supported by the fact that the ammonia abundance in the blueshifted gas is enhanced by a factor of \(\approx5\) with respect to the dense quiescent gas.

Subject headings: ISM: individual (L1157) — ISM: jets and outflows — ISM: molecules — shock waves — stars: formation

1. INTRODUCTION

The inversion lines of metastable ammonia have been extensively used for observations of dense \((\approx10^4\text{ cm}^{-3})\) molecular cloud cores (e.g., Myers & Benson 1983; Benson & Myers 1989), while the fractional abundance of \(\text{NH}_3\) varies among the clouds (Benson & Myers 1983). On the basis of a systematic survey, Suzuki et al. (1992) pointed out that \(\text{NH}_3\) tends to be more abundant in the star-forming cores than the starless cores. Such a trend is interpreted in terms of the gas–phase chemical evolution, which predicts that the \(\text{NH}_3\) is deficient in the early stages of chemical evolution and becomes abundant in the later stages (e.g., Herbst & Leung 1989; Suzuki et al. 1992). In addition to the gas–phase chemical evolution, the gas–gran interaction is also considered to be important for the abundance variation of \(\text{NH}_3\) (e.g., d’Hendecourt, Allamandola, & Greenberg 1985; Brown & Charnley 1990; Nejad, Williams, & Charnley 1990; Flower, Pineau des Forêts, & Walmsley 1995). In the star-forming dense cores, the \(\text{NH}_3\) molecules retained on dust grains can be released into the gas phase by means of shock waves caused by the outflow and the radiation from the newly formed star (e.g., Nejad et al. 1990; Flower et al. 1995) and are expected to contribute toward increasing the \(\text{NH}_3\) abundance.

Usually, it is not easy to estimate the contribution of molecules desorbed from dust grains from those formed in the gas phase. However, in the case of \(\text{NH}_3\), an ortho-to-para ratio of \(\text{NH}_3\) provides us with such information. Ammonia has two distinct species, ortho-\(\text{NH}_3\) \((K = 3n)\) and para-\(\text{NH}_3\) \((K \neq 3n)\), which arise from different relative orientations of the three hydrogen spins. The ortho-to-para ratio is expected to be the statistical equilibrium value of 1.0 when the \(\text{NH}_3\) molecules are formed in the processes of gas-phase reactions or grain surface reactions. This is because the reactions that form the \(\text{NH}_3\) molecule release large excess energies compared to the energy difference between the lowest ortho and para states, which make the ortho-to-para ratio close to the statistical value. However, the ortho-to-para ratio is expected to be larger than unity when the \(\text{NH}_3\) molecules adsorbed on grain surfaces are released into the gas phase with excess energy for desorption, which is comparable to the energy difference between the ortho and para states. This is because the lowest energy level of the para species is \(23\) K higher than that of the ortho species; para species require more energy for desorption than ortho species. The timescale of the interconversion between ortho-\(\text{NH}_3\) and para-\(\text{NH}_3\) is considered to be a order of \(10^6\) yr in the gas phase (Cheung et al. 1969). Therefore, the ortho-to-para ratio provides us with valuable information on physical conditions and chemical processes when the \(\text{NH}_3\) molecules are released into the gas phase.

Since the lowest energy level of ortho-\(\text{NH}_3\), \((J, K) = (0, 0)\), has no inversion doubling, it is necessary to observe the transitions higher than \((J, K) = (3, 3)\) to measure the ortho-to-para ratio. Such high transitions are hardly excited in the dark clouds of low temperature; however, recent observations have revealed that shocked gas associated with molecular outflows in the dark clouds is heated enough to excite the transitions higher than \((J, K) = (3, 3)\). One of the prototypical objects with shock-heated gas is the bipolar outflow in the dark cloud L1157 (e.g., Umemoto et al. 1992), which is located at 440 pc from the Sun (Vietti 1969). Previous \(\text{NH}_3\) observations have revealed that the gas in the outflow is heated to more than 50–100 K (Bachiller, Martin-Pintado, & Fuente 1993; Tafalla & Bachiller 1995). A good morphological coincidence of the \(\text{NH}_3\) distribution (Tafalla & Bachiller 1995) with that of the SiO \((J = 2\rightarrow1)\) emission (Zhang et al. 1995; Gueth, Guilloteau, & Bachiller 1998), which is considered to be a good tracer of the shocked molecular gas, reveals that the hot ammonia arises from the shocked gas. The \(\text{NH}_3\) abundance enhancement observed in the shocked gas (Tafalla & Bachiller 1995) suggests the possibility that the \(\text{NH}_3\) retained on grain mantles is released into the gas phase by means of shocks.
In this Letter, we report the observations of six metastable inversion lines of NH$_3$ from $(J, K) = (1, 1)$ to (6, 6) toward the blueshifted lobe of the L1157 outflow. We have detected the high-excitation NH$_3$ (5, 5) and (6, 6) lines for the first time in the low-mass star-forming regions. Of six observed transitions, the (3, 3) and (6, 6) states belong to ortho-NH$_3$ and the other four states belong to para-NH$_3$. The detection of both (6, 6) and (3, 3) emission enables us to measure the ortho-to-para ratio, which provides us with information on the contribution of ammonia molecules desorbed from grains.
and weak (2, 2) and (3, 3) lines are observed. No emission from the transitions higher than (4, 4) has been detected. The (1, 1) line observed at position A shows the quiescent component peaked at $V_{lsr} = 2.85$ km s$^{-1}$, which is almost the same as the cloud systemic velocity of $≈2.7$ km s$^{-1}$ derived from the 13CO observations (Umemoto et al. 1992), with a weak blueshifted wing. The (2, 2) and (3, 3) lines appear in the velocity range of the (1, 1) wing emission, suggesting that these line profiles are contaminated by the blueshifted component in the southern lobe because of the large beam size of $72''$. Since the (2, 2) and (3, 3) lines show no significant emission at the velocity of the quiescent component, the rotational temperature $T_{rot}$ of the quiescent component is estimated to be $≤10$ K.

At positions B and C, all six transitions up to (6, 6) were detected. The (5, 5) and (6, 6) lines are first detected in the low-mass star-forming regions. All transition lines except the (1, 1) one have peak velocities blueshifted by $1–2$ km s$^{-1}$ from the cloud systemic velocity and show broad widths of $ΔV ≈ 4–10$ km s$^{-1}$ (measured at the 1 $σ$ level), indicating that the emission of the higher energy level arises from the high-velocity gas. The (3, 3) line profiles at positions B and C resemble the profiles of the SiO ($J = 2–1$) and CS ($J = 2–1$) lines observed by Miyatake et al. (1992). Among the six transition lines, the (3, 3) line is the strongest, as previously pointed out by Bachiller et al. (1993). The peak brightness temperatures of the (2, 2), (3, 3), and (4, 4) lines observed at position B are lower by a factor of 1.5–2 than those observed by Bachiller et al. (1993) at the same position. This may be due to the beam dilution effect, since the spatial extent of the ammonia-emitting area is smaller than our beam (Bachiller et al. 1993; Tafalla & Bachiller 1995).

Toward three other positions outside the blueshifted lobe, we have detected only the (1, 1) emission line at the systemic velocity.

4. DISCUSSION

4.1. Temperature and Ortho-to-Para Ratio of the High-Velocity Gas

To obtain the rotational temperature $T_{rot}$ of the blueshifted gas, we assumed optically thin emission and constructed rotation diagrams, i.e., the logarithms of NH$_3$ column densities divided by the statistical weight of the transition, plotted against the energy above the ground state. The contribution of the quiescent component in the (1, 1) line was eliminated by performing a multicomponent Gaussian fitting. The rotational temperature estimated from the (1, 1) and (2, 2) data, $T_{rot}(1, 1; 2, 2)$, is 38 K at position B and 48 K at position C. These temperatures are a factor of 4–5 higher than that of the quiescent component at position A. Figure 3 shows that the $T_{rot}$'s obtained from the data of higher transitions are significantly higher than $T_{rot}(1, 1; 2, 2)$. The rotational temperatures obtained from the para-NH$_3$ (4, 4) and (5, 5) data, $T_{rot}(4, 4; 5, 5)$, are $≈130$ K for both positions B and C. The slopes between the ortho-NH$_3$ (3, 3) and (6, 6) data are almost parallel to those between the para-NH$_3$ (4, 4) and (5, 5) ones, indicating that $T_{rot}(3, 3; 6, 6)$ is comparable to $T_{rot}(4, 4; 5, 5)$.

It should be noted that the column densities of the ortho species are higher than those of the para species; this suggests that the ortho species are more abundant than the para species. If we assume an ortho-to-para ratio of $≈1.5$, the data of four transitions involving the ortho and para states align on the straight lines; the best fits provide an ortho-to-para ratio at position B of $1.7^{+0.3}_{−0.5}$ and at position C of $1.3 ± 0.2$. Then we obtain a $T_{rot}$ at position B of $140^{+4}_{−4}$ K (the upper and lower limit of the $T_{rot}$ correspond to those of the ortho-to-para ratio, respectively) and at position C of $125^{+4}_{−3}$ K.

The discrepancy between the $T_{rot}(1, 1; 2, 2)$ and the $T_{rot}$ derived from the higher transition data can be explained by two components of gas with different kinetic temperatures, as suggested by Avery & Chiao (1996) from their SiO observations. However, we consider that most of the gas traced by the NH$_3$ emission is heated to 130–140 K for the following reason. It is known that the metastable populations may deviate from a true Boltzmann distribution due to collisional depopulation of the higher nonmetastable levels. As argued by Danby et al. (1988), the $T_{rot}$ tends to underestimate the gas kinetic temperature $T_k$ at the $T_k$ range higher than $≈30$ K. Since the difference is remarkable for the $T_{rot}$ derived from the lower $J$ transitions, the $T_{rot}$ estimated from the higher transitions is considered to be a better indicator of the kinetic temperature than $T_{rot}(1, 1; 2, 2)$. These two rotational temperatures were also observed in the M17SW molecular cloud (Güsten & Fiebig 1988).
4.2. Ammonia Abundance Enhancement

The beam-averaged NH$_3$ column density in the quiescent gas at position A is estimated to be $N$(NH$_3$) = 2 × 10$^{14}$ cm$^{-2}$. When we employed the H$_2$ column density of the ambient gas derived from the $^{13}$CO and C$^{18}$O observations [$N$(H$_2$) = 3 × 10$^{21}$ cm$^{-1}$], the NH$_3$ abundance for the quiescent component is estimated to be $X$(NH$_3$) = 7 × 10$^{-8}$, which is comparable to those measured in nearby dense cores [$X$(NH$_3$) = (3–10) × 10$^{-8}$; Benson & Myers 1983]. The N(NH$_3$)'s in the blueshifted gas averaged over the beam at positions B and C are calculated to be 1 × 10$^{14}$ and 7 × 10$^{13}$ cm$^{-2}$, respectively. The H$_2$ column densities of the blueshifted gas were estimated from the CO ($J$ = 1–0) data obtained at the NRO 45 m telescope (the beam size was 16") by convolving the data with the 72" Gaussian beam and assuming the optically thin CO emission, $T_\text{A} = 130$ K, and a $^{12}$CO abundance ratio of 10$^4$. They are estimated to be 7 × 10$^{21}$ cm$^{-2}$ toward position B and 2 × 10$^{21}$ cm$^{-2}$ toward position C. By using these H$_2$ column densities, we obtained $X$(NH$_3$) = 1 × 10$^{-7}$ at position B and $X$(NH$_3$) = 3 × 10$^{-7}$ at position C, which are a factor of 2–5 higher than that of the quiescent component. The NH$_3$ column densities derived by Tafalla & Bachiller (1995) from their high-resolution VLA data are ~5 × 10$^{14}$ cm$^{-2}$ toward both positions B and C. If we compare these $N$(NH$_3$) values with the $N$(H$_2$) values—which are 2 × 10$^{20}$ cm$^{-2}$ for position B and 8 × 10$^{20}$ cm$^{-2}$ for position C in the 16" beam derived from the CO ($J$ = 1–0) data by assuming an excitation temperature of 130 K—we obtain $X$(NH$_3$) = 3 × 10$^{-7}$ and $X$(NH$_3$) = 7 × 10$^{-7}$ for positions B and C, respectively. The H$_2$ column densities used here may be somewhat underestimated because the sizes of the NH$_3$ enhanced regions (~10") in the map of Tafalla & Bachiller (1995) are smaller than the beam size of the CO data. When we take this into account, the ammonia abundances obtained from the higher resolution data are consistent with those from the 72" resolution data. Therefore, we conclude that the NH$_3$ abundance in the shocked regions is enhanced by a factor of ~5.

4.3. Ortho-to-Para Ratio and Its Implication for the Contribution of Desorbed Ammonia

The derived ortho-to-para ratio in the blueshifted gas, which is larger than the statistical value of 1.0, suggests that a significant amount of NH$_3$ observed in the blueshifted gas has been evaporated from dust grains. The evaporation of ammonia is supported by the fact that the ammonia abundance is enhanced in the blueshifted gas. If we assume that all of the NH$_3$ molecules observed in the blueshifted gas were from dust grains, the observed ratio of 1.3–1.7 suggests that the population of the rotational levels of NH$_3$ at the time of ejection from the grain surface is represented by a Boltzmann distribution with a temperature of 18–25 K. This formation temperature would be related to the excess energy distributed to the rotational degree of freedom in desorption processes and is not necessarily equal to the dust temperature or the gas kinetic temperature (Takayanagi, Sakimoto, & Onda 1987). It is most likely that the NH$_3$ molecules retained on grains have been provided with sufficient energy to desorb from the grain surfaces by the passage of shocks (e.g., Nejad et al. 1990; Flower et al. 1995). The rotational temperature of 130–140 K suggests that the shock heating may be responsible for the desorption of the NH$_3$ molecules. Sandford & Allamandola (1993) revealed that the sublimation of ammonia drastically increases as a function of temperature: the residence time of NH$_3$ on a dust grain that is 10$^5$ yr at 40 K becomes only 10$^{-7}$ yr at 100 K.

Recently, the infrared spectroscopic observations with Infrared Space Observatory and ground-based telescopes reported that the abundance of the solid NH$_3$ (relative to H$_2$O) in icy grain mantles is no more than a few percent (e.g., Whittet et al. 1996a, 1996b). These results imply that the NH$_3$ molecule desorbed from grains is less important than previously expected (e.g., d’Hendecourt et al. 1985; Brown & Charnley 1990; Nejad et al. 1990). However, the ortho-to-para ratio measured in the L1157 outflow indicates that a significant amount of NH$_3$ arises from dust grains and that the gas-grain chemistry plays an important role in determining the NH$_3$ abundance.

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