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DETECTION OF INTERSTELLAR N_2O: A NEW MOLECULE CONTAINING AN N–O BOND

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ABSTRACT

A new interstellar molecule, N_2O, known as nitrous oxide or "laughing gas," has been detected using the NRAO 12 m telescope. The $J = 3 \rightarrow 2$, $4 \rightarrow 3$, $5 \rightarrow 4$, and $6 \rightarrow 5$ rotational transitions of this species at 75, 100, 125, and 150 GHz, respectively, were observed toward Sgr B2(M). The column density derived for N_2O in this source is $N_{\rm tot} \sim 10^{15}$ cm^{-2}, which corresponds to a fractional abundance of $\sim 10^{-9}$, relative to H_2. This value implies abundance ratios of $N_2O/NO \sim 0.1$ and $N_2O/HNO \sim 3$ in the Galactic center. Such ratios are in excellent agreement with predictions of ion-molecule models of interstellar chemistry using early-time calculations and primarily neutral-neutral reactions. N_2O is the third interstellar molecule detected thus far containing an N–O bond. Such bonds cannot be so rare as previously thought.

Subject headings: ISM: abundances — ISM: Galaxy: center — ISM: molecules — line: identification

1. INTRODUCTION

The lack of N–O bonds has for many years been an apparent problem with interstellar nitrogen chemistry (e.g., Turner & Ziurys 1988). Until recently, there was only one molecule in the ISM that had been securely identified that contained such a bond, nitric oxide, or NO (Liszt & Turner 1978). Furthermore, this species was observed in one source, Sgr B2(OH). Searches had been carried out for other N–O bond bearing compounds, including HNO_3 (Giguere et al. 1973) and N_2O (Wilson & Snyder 1981), but with negative results. In addition, Ulich, Hollis, & Snyder (1977) conducted a search for interstellar HNO, and detected a line at the frequency of the 1_{01}–0_{00} rotational transition near 81 GHz toward SgrB2(OH). For many years, however, this identification could not be substantiated.

The lack of N–O bonds is only one of many problems pertaining to nitrogen chemistry. Another obvious discrepancy is the inability of chemical models to synthesize many simple *N*-containing species at early times, especially those containing N and H (Millar 1990). The early time calculations are generally most successful in reproducing observed molecular abundances, as opposed to those estimated by allowing the model to reach steady-state.

Very recent observations have given some insight into these chemical problems. First of all, HNO has been securely confirmed via additional measurements of the 1_{01}–0_{00} line at 81 GHz in several new sources (Snyder et al. 1993), and the detection of the 2_{02}–1_{01} and 3_{03}–2_{02} rotational transitions at 163 and 244 GHz in some of these same objects (Hollis et al. 1991; Ziurys, Hollis, & Snyder 1994). Furthermore, NO appears to be present with moderate abundances in many molecular clouds, including the dark cloud L134N (McGonagle et al. 1990) and various star-forming regions (Ziurys et al. 1991). In fact, NO and HNO are found in almost the same set of objects, suggesting that their chemistry is linked (Ziurys et al. 1994). Moreover, the abundances of both species are reproduced by early time model calculations. Their chemical behavior thus contrasts with other nitrogen-bearing species, in particular NH_3 and N_2H^+.

With the goal of better understanding of nitrogen chemistry, and establishing the true prevalence of N–O bonds, we have conducted a renewed search for interstellar N_2O (nitrous oxide, termed "laughing gas") toward the galactic center. We have detected the $J = 3 \rightarrow 2$, $4 \rightarrow 3$, $5 \rightarrow 4$, and $6 \rightarrow 5$ rotational transitions of this linear species toward Sgr B2(M) at 75, 100, 125, and 150 GHz. In this *Letter* we report our results and discuss its significance for the N–O chemistry.

2. OBSERVATIONS

The measurements of N_2O were carried out in 1994 May/June, using the NRAO[3] 12 m telescope located at Kitt Peak, Arizona. Observing frequencies and beam efficiencies η_c are listed in Table 1. Beam sizes at 75, 100, 125, and 150 GHz were 85″, 63″, 48″ and 42″, respectively. The three receivers used were dual-channel, cooled SIS mixers, operated in a single-sideband mode with at least 20 dB rejection, obtained by tuning the mixers. The temperature scale was determined by the chopper-wheel method, corrected for forward spillover losses, and is given in terms of T_R^*. The radiation temperature, T_R, assuming the source fills only the main telescope beam, is then $T_R = T_R^*/\eta_c$. The backends employed were two filter banks with 256 channels each, used in a parallel mode (2 × 128 channels) with both receiver channels. Filter resolutions were 500/250 kHz for 75 and 100 GHz observations, and 1000/500 kHz for the 125 and 150 GHz measurements. Data were taken in a position-switching mode with pointing determined by

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[3] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

OBSERVATIONS OF N_2O TOWARD Sgr B2(M)[a]

Transition	Frequency[b] (MHz)	η_c	T_R^* (K)[c]	V_{LSR}[c] (km s^{-1})	$\Delta v_{1/2}$[c] (km s^{-1})	Resolution (MHz)
$J = 3 \rightarrow 2$.......	75,369.2	0.92	0.030 + 0.010	63.1 ± 2.0	11.1 ± 2.0	0.5
$J = 4 \rightarrow 3$[d]......	100,491.7	0.86	0.038 ± 0.010	63.1 ± 1.5	12.6 ± 1.5	0.5
$J = 5 \rightarrow 4$.......	125,613.7	0.80	0.067 ± 0.010	62.5 ± 2.4	11.2 ± 2.4	1.0
$J = 6 \rightarrow 5$.......	150,735.0	0.72	0.065 ± 0.010	61.1 ± 2.0	14.2 ± 2.0	1.0

[a] $\alpha = 17^h44^m11^s.0$; $\delta = -28°22'00''$ (1950.0); all errors are 3 σ.

[b] Frequencies from Lovas 1978.

[c] Determined from Gaussian fits to the data.

[d] Reconstructed spectrum (see text).

observations of planets. Local oscillator shifts were performed at all observing frequencies. The position used for Sgr B2(M) was $\alpha = 17^h44^m11^s.0$; $\delta = -28°22'00''$ (1950.0).

3. RESULTS

The results of the observations are shown in Figure 1, which presents the four transitions detected. As the figure shows, the $J = 3 \rightarrow 2$, $5 \rightarrow 4$, and $6 \rightarrow 5$ lines appear to be uncontaminated by other spectral features. The $J = 4 \rightarrow 3$ transition, however, is blended with the 8(1, 7)–(1, 6) A transition of methyl formate at 100,490.5 MHz. The 8(1, 7)–7(1, 6) E line of methyl formate lies close-by in frequency at 100,482.3 MHz, as is shown in Figure 2. Both the E and A transitions of $HCOOCH_3$ should have equal intensity (Bauder 1979). As Figure 2 illustrates, the A line must be blended with another feature, presumably N_2O, because both its intensity and linewidth are larger than its E counterpart. The spectral line for the $J = 4 \rightarrow 3$ transition was obtained by removing the contribution of the $HCOOCH_3$ 8(1, 7)–(1, 6) A line. The $HCOOCH_3$ E line was modeled with a Gaussian profile and this Gaussian was subtracted from the spectrum composed of $HCOOCH_3$ A and N_2O to produce the resulting feature shown in Figure 1.

As is also shown in the spectra, several unidentified lines were observed in addition to N_2O. U100509 appears in the $J = 4 \rightarrow 3$ spectrum. This line could also possibly arise from the 22(3, 19)–22(3, 20) transition of H_2CO if there is sufficient excitation in Sgr B2(M). In the $J = 5 \rightarrow 4$ data, two U-lines (U125603 and U125621) are apparent as well.

Table 1 presents the line parameters for each spectrum, which were obtained by Gaussian fits to the profiles. As the table illustrates, both the LSR velocities and linewidths are in good agreement with each other, even for the deconvolved

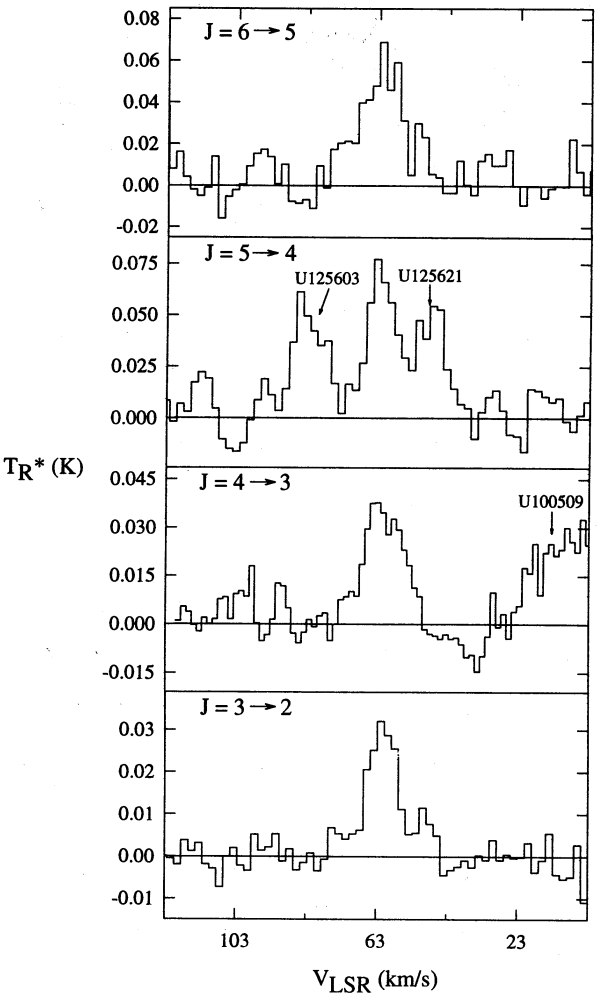

FIG. 1.—Spectra of the $J = 6 \rightarrow 5$, $5 \rightarrow 4$, $4 \rightarrow 3$, and $3 \rightarrow 2$ rotational transitions of N_2O, detected toward Sgr B2(M) using the NRAO 12 m telescope. The $J = 6 \rightarrow 5$ and $5 \rightarrow 4$ lines were measured with 1 MHz resolution, and the $4 \rightarrow 3$ and $3 \rightarrow 2$ transitions with 500 kHz resolution. Also present in the data are several U-lines. (The $J = 4 \rightarrow 3$ line profile is a reconstructed spectrum obtained by removing a contaminating $HCOOCH_3$ line; see text and Fig. 2).

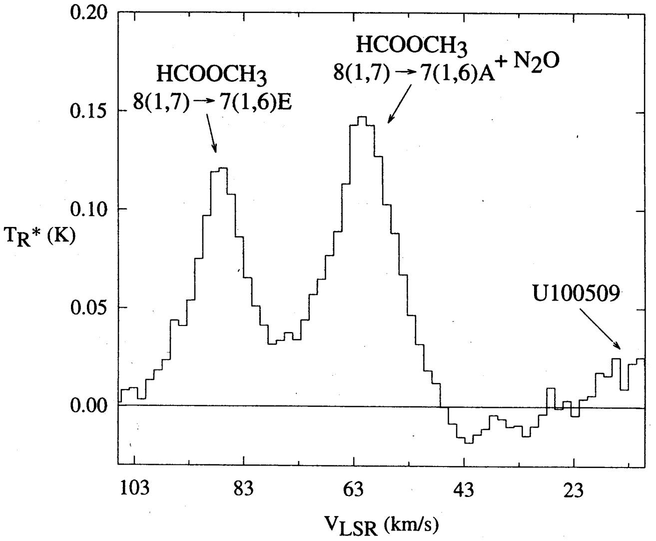

FIG. 2.—Spectrum of the $HCOOCH_3$ 8(1, 7)–7(1, 6) E and A transitions, the latter which is blended with the $J = 4 \rightarrow 3$ line of N_2O, observed toward Sgr B2(M). Filter resolution is 500 kHz. Subtraction of the A line profile from the blended spectrum resulted in the $J = 4 \rightarrow 3$ spectrum of N_2O shown in Fig. 1.

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$J = 4 \rightarrow 3$ line. The velocities range from 61.1 to 63.1 km s^{-1}, with an average of $V_{LSR} \sim 62.5$ km s^{-1}. The linewidths vary from 11.1 to 14.2 km s^{-1}, yielding an average of $\Delta v_{1/2} \sim 12.3$ km s^{-1}. In addition, there are no inconsistencies in the intensities of the four lines. N_2O was also detected toward Sgr B2(N), and possibly W51M. These measurements will be described in a later paper.

4. DISCUSSION

4.1. N_2O *Column Density and Abundance*

N_2O is a linear molecule with a $^1\Sigma$ ground state; hence, column densities are easily calculated. These values were determined from the line parameters measured for each transition using the following formula, which assumes low optical depth:

$$N_{\rm tot} = \frac{3k10^5 e^{h\nu/kT_{\rm ex}} Q_{\rm rot}\, T_R\, \Delta v_{1/2}}{8\pi^3 \nu \mu_0^2 (J+1) e^{-\Delta E_{\rm gd}/T_{\rm rot}}}: J+1 \rightarrow J\ . \qquad (1)$$

In the expression, ν is the frequency of the transition, μ_0 the permanent dipole moment (0.16 D), $Q_{\rm rot}$ the rotational partition function, $\Delta E_{\rm gd}$ the energy of the Jth level above ground state, and T_R and $\Delta v_{1/2}$ the radiation temperature and linewidth. The terms $T_{\rm ex}$ and $T_{\rm rot}$ are the excitation and rotational temperatures, respectively. It was assumed that $T_{\rm ex} = T_{\rm rot}$, i.e., the lines are "thermalized". This assumption is reasonable, considering the small dipole moment for N_2O of 0.16 D. The rotational temperature was chosen to be 36 K, based on kinetic temperatures determined for Sgr B2(M) (Lis & Goldsmith 1991).

Using this formula, the total column densities for N_2O were determined to be 0.75–1.1 × 10^{15} cm^{-2}, depending on which transition is used, for an average of $\sim 10^{15}$ cm^{-2}. The lack of scatter between individual column densities further supports the notion that all lines observed arise from N_2O, and that the assumption of $T_{\rm ex} = T_{\rm rot} = 36$ K is reasonable. Rotational diagram fits to the data were also made. Varying the source size caused the rotational temperature to vary from ~12 to 150 K, but made only small changes (less than a factor of 2) in the column density. Hence, the value of $N_{\rm tot} \sim 10^{15}$ cm^{-2} is probably a very reasonable estimate of this quantity. Taking the H_2 column density of 10^{24} cm^{-2} for Sgr B2(M) (Goldsmith, Snell, & Lis 1987b; Goldsmith et al. 1987a), the fractional abundance of N_2O is $f \sim 10^{-9}$.

These derived values are consistent with the upper limits obtained by Wilson & Snyder (1981). These authors obtained $N_{\rm tot}(N_2O) < 10^{15}$ cm^{-2} for $T_{\rm rot} = 20$ K, but toward Sgr B2(OH). This position is 30″ south of Sgr B2(M), but is contained in the 3 mm beam of the 12 m telescope.

4.2. *Lack of Interstellar* N–O *Bonds?*

The detection of interstellar N_2O is additional evidence that the dearth of N–O bonds may be exaggerated. Although these observations focus on Sgr B2(M), there is strong evidence that nitrous oxide is present in Sgr B2(N) and perhaps throughout the Galactic center clouds. It may exist in W51 as well, and in other sources. Certainly additional measurements need to be carried out to evaluate the extent of N_2O emission in interstellar gas. Like NO and HNO, this molecule may be a common constituent in dense clouds.

Nitric oxide (NO) has thus far been observed in six molecular clouds: Sgr B2(N)/(OH), Orion-KL, W33, W51M, DR 21(OH), and L134N (McGonagle et al. 1990; Ziurys et al. 1991). HNO has been detected in six sources as well—almost the identical list as for NO with the exception of Orion-KL. In this object only an upper limit has been obtained for HNO (Snyder et al. 1993). Furthermore, N_2O has been discovered toward the Galactic center, i.e., in the object where both NO and HNO are the most abundant. Thus, interstellar molecules containing N–O bonds do appear to be rather common. It is likely that more such species will be detected in the future, provided careful searches are conducted.

4.3. *Relationship of* N_2O, HNO, *and* NO

N_2O was detected toward Sgr B2(M), where HNO has its highest fractional abundance of 3.2 × 10^{-10} (Ziurys et al. 1994). Thus, the ratio of N_2O/HNO is ~3 in this gas. For NO, a fractional abundance at the Sgr B2(M) position has not been measured. The Sgr B2(N) cloud [$\alpha = 17^h44^m09^s.4$; $\delta = -28°21'20''$ (1950.0)] and Sgr B2(OH) position [$\alpha = 17^h44^m11^s.0$; $\delta = -28°22'30''$ (1950.0)], however, have been observed in NO, yielding abundance of NO/H_2 ~ 1.1 × 10^{-8} and 0.75 × 10^{-8}, respectively. Because Sgr B2(M) lies approximately between these two regions (see Snyder et al. 1993), using an average of the two abundances is perhaps a valid comparison. This average value is ~0.9 × 10^{-8}, yielding an N_2O/NO ratio of ~0.1. Thus, while NO is still more abundant than nitrous oxide, the HNO and N_2O concentrations are comparable, at least in the Galactic center. This result is curious, since N_2O is closed-shell and hence the most stable of the three species, while both NO and HNO are free radicals and far more reactive. If thermodynamics governed the chemistry rather than kinetics, N_2O would be more abundant than NO or HNO.

Unfortunately, there is only one quiescent cloud, ion-molecule abundance calculation for N_2O in the recent literature for comparison, that of Millar et al. (1991). Such a comparison is of interest, because it is likely that N_2O is extended and should be produced chiefly by this type of chemistry. Millar et al. (1990) predict $f(N_2O) \sim 2.6 \times 10^{-10}$ at early times and 2.3 × 10^{-8} at steady state. Thus, the best agreement between theory and observation for the N_2O abundance is the early time value, which is only a factor of 3 less than that observed. They also calculate N_2O/NO ~ 0.06 and N_2O/HNO ~ 1 and give NO/HNO ~ 17, again at early times. Considering the estimated NO/HNO ratio of ~30 in Sgr B2(M), the model predictions for the NO, HNO, and N_2O relative abundances are in very good agreement with observed values for early times as well. At steady state, the calculations do not fit the observations nearly as closely, with N_2O/NO ~ 0.7, N_2O/HNO ~ 2, and NO/HNO ~ 3. Thus, N_2O/NO and NO/HNO ratios differ significantly from the measured quantities in the steady state case.

Millar et al. (1991) show that the N_2O is produced and destroyed via neutral-neutral and ion-molecule processes. N_2O appears to primarily form from NO_2 via the following reaction, with $k_1 \sim 2 \times 10^{-11}$ cm^3 s^{-1}:

$$N + NO_2 \xrightarrow{k_1} N_2O + O\ . \qquad (2)$$

NO_2 also leads to NO by the process:

$$N + NO_2 \xrightarrow{k_2} 2NO\ , \qquad (3)$$

where $k_2 \sim 7 \times 10^{-12}$ cm^3 s^{-1}. The destruction of N_2O occurs through ion-molecule reactions with O^+ and He^+, at approximately the Langevin rate ($k \sim 10^{-9}$ cm^3 s^{-1}):

$$N_2O + O^+ \rightarrow NO^+ + NO \qquad (4)$$

$$N_2O + He^+ \rightarrow N_2^+ + O + He \qquad (5)$$

Thus, the chemistries of N_2O and NO appear to be linked. NO also leads to HNO via (see Ziurys, Hollis, & Snyder 1994):

$$HNO^+ + NO \rightarrow HNO + NO^+ \qquad (6)$$

Hence, all three molecules are synthesized in the same reaction network and should be found in the same gas, as supported by our observations.

5. CONCLUSION

While some aspects of nitrogen chemistry are not understood, our detection of interstellar N_2O has put some constraints on the N/O chemical network. The relative abundances now determined for N_2O, HNO, and NO in Sgr B2 appear to be reasonably well predicted by quiescent cloud, ion molecule type chemistry at early times. Steady state predictions are not necessary to explain the concentrations of these three related nitrogen-bearing species. Further studies of N_2O in other clouds will be useful for a more general assessment of nitrogen chemistry, as well as establish the prevalence of N – O bonds.

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