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THE DETECTION OF EXTRAGALACTIC ^{15}N: CONSEQUENCES FOR NITROGEN NUCLEOSYNTHESIS AND CHEMICAL EVOLUTION[1]

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ABSTRACT

Detections of extragalactic ^{15}N are reported from observations of the rare hydrogen cyanide isotope HC^{15}N toward the Large Magellanic Cloud (LMC) and the core of the (post-)starburst galaxy NGC 4945. Accounting for optical depth effects, the LMC data from the massive star-forming region N113 infer an ^{14}N/^{15}N ratio of 111 ± 17, which is about twice the ^{12}C/^{13}C value. For the LMC star-forming region N159HW and for the central region of NGC 4945, ^{14}N/^{15}N ratios are also ≈ 100. The ^{14}N/^{15}N ratios are smaller than all interstellar nitrogen isotope ratios measured in the disk and center of the Milky Way, strongly supporting the idea that ^{15}N is synthesized by massive stars. Although this appears to be in contradiction with standard stellar evolution and nucleosynthesis calculations, it supports recent findings of abundant ^{15}N production due to rotationally induced mixing of protons into the helium-burning shells of massive stars.

Subject headings: galaxies: abundances — galaxies: starburst — ISM: abundances — ISM: molecules — Magellanic Clouds — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Carbon, nitrogen, and oxygen, the "CNO elements," are among the most abundant species after hydrogen and helium. Being formed by *p*- and α-capture reactions in the interior of stars, the CNO nuclei are partially released by means of stellar winds, planetary nebula ejecta, and supernova explosions into the interstellar medium (ISM). ^{12}C and ^{16}O and, qualitatively, ^{13}C and ^{17}O nucleosynthesis appears to be understood (e.g., Wilson & Matteucci 1992; Henkel & Mauersberger 1993; Henkel et al. 1994b; Prantzos, Aubert, & Audouze 1996). The dominant cooking site of the rare nitrogen isotope ^{15}N is, however, not yet known. While ^{14}N is produced in both high-mass and lower mass stars, it is not yet clear whether ^{14}N or ^{15}N is the more "primary" isotope (see § 4).

To obtain new constraints for nitrogen nucleosynthesis, we measured ^{14}N/^{15}N abundance ratios in molecular environments that have not yet been explored. The molecular studies by Johansson et al. (1994), Chin et al. (1996, 1997, 1998), and Heikkilä et al. (1997, 1998) demonstrate that it is possible to detect rare molecular species in the Magellanic Clouds. Since such metal-poor environments may also characterize cosmologically relevant sources at high redshift, we searched for HC^{15}N in three Magellanic star-forming regions showing prominent H^{12}C^{14}N (hereafter HCN) emission. In view of the low ^{14}N/^{15}N ratios predicted by Henkel & Mauersberger (1993) and Henkel et al. (1994b) for starbursts, we also searched for HC^{15}N in the southern (post-)starburst galaxy NGC 4945.

2. OBSERVATIONS

The data were taken in 1997 September and November and in 1998 January and July using the 15 m Swedish-ESO Submillimeter Telescope at La Silla, Chile. A 3 mm SIS receiver yielded overall system temperatures, including sky noise, of order $T_{\rm sys} = 250$ K on a main-beam brightness temperature ($T_{\rm MB}$) scale. The back end was an acousto-optical spectrometer (AOS). A channel separation of 42 kHz corresponding to 0.14 km s^{-1} at 88 GHz was employed for the observations toward the Magellanic Clouds, while the low-resolution spectrometer with a channel separation of 0.7 MHz (or 2.4 km s^{-1}) was used for NGC 4945. The antenna beamwidth was 55″ at the observed line frequencies taken from Lovas (1992).

The observations were carried out in a dual beam-switching mode (switching frequency 6 Hz) with a beam throw of 11′40″ in azimuth. All spectral intensities were converted to a $T_{\rm MB}$ scale, correcting for a main-beam efficiency of 0.76 (L. B. G. Knee, L.-Å. Nyman, & A. R. Tieftrunk 1998, private communication). Calibration was checked by monitoring on Orion KL and NGC 4945 and was found to be consistent between different observation periods within ±10%. The pointing accuracy, obtained from measurements of the SiO masers R Dor and W Hya, was better than 10″.

3. RESULTS

Toward the prominent LMC star-forming regions N113 and N159HW, we have detected the $J = 1$–0 emission lines of hydrogen cyanide (HCN) and its rare isotopic species H^{13}CN and HC^{15}N. Although they were also detected toward the core of the (post-)starburst galaxy NGC 4945 (e.g., Koornneef 1993), only HCN was seen in the SMC star-forming region LIRS 36 (see Chin et al. 1998). Spectra and line parameters obtained from Gaussian fits are displayed in Figure 1 and Table 1. Observed line intensity ratios (R, R_{02}, R_{12}), derived opacities (τ_0), and isotopic abundance ratios (^{12}C/^{13}C and ^{14}N/^{15}N) are given in Table 2.

Apart from optical depth effects, integrated line intensity ratios should be identical to isotope ratios within the observational errors, since rotational constants of the various HCN isotopomers are similar. A fractionation of nitrogen isotopes

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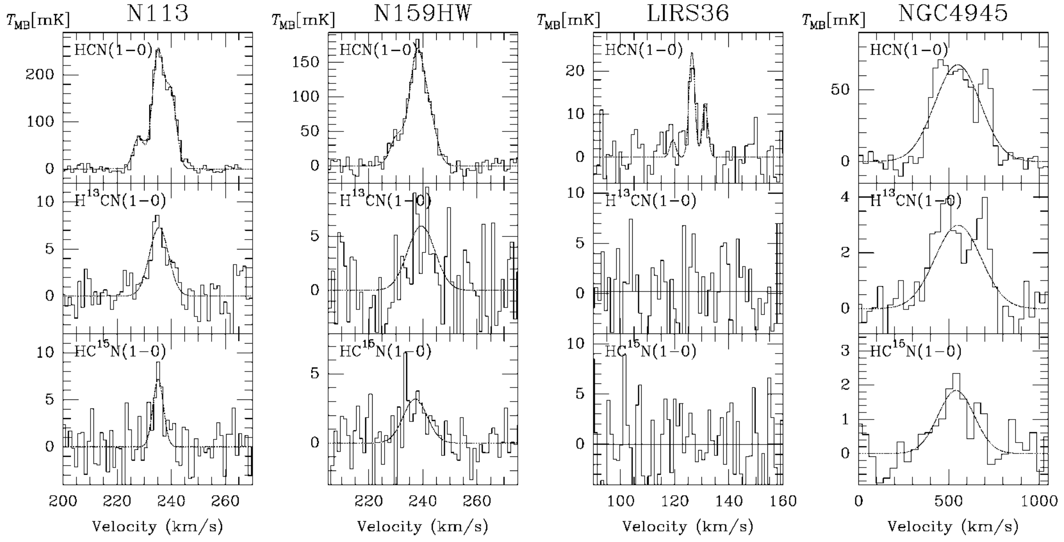

FIG. 1.—Spectra of HCN, H^{13}CN, and HC^{15}N; for coordinates, see Chin et al. (1997) and Henkel, Whiteoak, & Mauersberger (1994a)

via charge exchange reactions, as expected in the case of carbon (see Watson, Anicich, & Huntress 1976), must be negligible, because the nitrogen ionization potential is higher than that of hydrogen; N^{+} abundances are small in molecular clouds. For the two LMC star-forming regions and for NGC 4945, we then find ^{14}N/^{15}N ≈ 100. In the case of N113, the ^{14}N/^{15}N ratio does not depend on an assumption on ^{12}C/^{13}C. Instead, ^{14}N/^{15}N is *directly* derived from the HCN/HC^{15}N integrated line temperature ratio and from a fit to the HCN hyperfine components (see Table 2). Toward N159HW, the HCN main line also appears to be almost optically thin, but a larger intrinsic line width makes the fit less convincing.

4. DISCUSSION

Observations indicate that ^{14}N production involves both a primary and a secondary component (e.g., Matteucci 1986; Vila-Costas & Edmunds 1993; van Zee et al. 1998), which is

TABLE 1

MOLECULAR LINE PARAMETERS

Molecule	Transition	Frequency (GHz)	T_{MB} (mK)	rms[a] (mK)	v_{LSR} (km s^{-1})	$\Delta v_{1/2}$ (km s^{-1})	$\int T_{MB}dv$ (K km s^{-1})
			N113				
HCN [b]	J = 1–0 F = 1–1	88.630416	158	11	235.0	4.8	0.809 ± 0.057
	F = 2–1	88.631847	246	11	235.0	4.8	1.26 ± 0.06
	F = 0–1	88.633936	68	11	235.0	4.8	0.346 ± 0.057
H^{13}CN [c]	J = 1–0	86.340184	7.3	3	235.4	8.3	0.065 ± 0.004
HC^{15}N [c]	J = 1–0	86.054961	7.2	3	235.2	4.6	0.035 ± 0.004
			N159HW				
HCN [b]	J = 1–0 F = 1–1	88.630416	65	13	237.7	6.2	0.425 ± 0.087
	F = 2–1	88.631847	156	13	237.7	6.2	1.03 ± 0.09
	F = 0–1	88.633936	43	13	237.7	6.2	0.283 ± 0.087
H^{13}CN [c]	J = 1–0	86.340184	5.9	5	239.4	12.0	0.076 ± 0.009
HC^{15}N [c]	J = 1–0	86.054961	3.2	3	237.2	10.4	0.035 ± 0.005
			LIRS 36				
HCN [b]	J = 1–0 F = 1–1	88.630416	12	7	126.4	2.5	0.032 ± 0.018
	F = 2–1	88.631847	25	7	126.4	2.5	0.066 ± 0.019
	F = 0–1	88.633936	4		126.4	2.5	0.011 ± 0.018
H^{13}CN [c]	J = 1–0	86.340184	<5	6	...	...	<0.020 [d]
HC^{15}N [c]	J = 1–0	86.054961	<5	6	...	...	<0.024 [d]
			NGC 4945				
HCN	J = 1–0	88.631847	67	11	550	300	21.3 ± 0.1
H^{13}CN	J = 1–0	86.340184	3.0	1	550	300	0.959 ± 0.013
HC^{15}N	J = 1–0	86.054961	1.8	1	540	250	0.464 ± 0.012

[a] 1 σ noise level of a single channel width of 0.14 km s^{-1} (for the Magellanic Clouds) or 2.4 km s^{-1} (for NGC 4945) on a T_{MB} scale.

[b] The three HCN hyperfine transitions (F = 1–1, F = 2–1, F = 0–1) have been resolved by a Gaussian fit. While T_{MB} values and integrated line intensities are given for each component, the velocity refers to the main component.

[c] The hyperfine components of H^{13}CN and HC^{15}N cannot be resolved.

[d] For undetected lines, 3 σ values are given.

TABLE 2

Results Derived from Table 1

Source	R(HCN/H^{13}CN)	R(HCN/HC^{15}N)	R(H^{13}CN/HC^{15}N)	R_{12}[a]	R_{02}[a]	τ_0[a]	^{12}C/^{13}C	^{14}N/^{15}N
N113	37 ± 5	69 ± 13	1.9 ± 0.3	0.64 ± 0.07	0.27 ± 0.06	0.122	60 ± 6	111 ± 17
N159HW	23 ± 6	49 ± 15	2.1 ± 0.6	0.41 ± 0.12	0.27 ± 0.11	<1	≈50 [b]	≈100 [c]
LIRS 36	>4.5	>5.5	…	0.49 ± 0.41	0.17 ± 0.32	…	…	…
NGC 4945	22 ± 1	46 ± 1	2.1 ± 0.1	…	…	<1	≈50 [b]	≈100 [c]

[a] The opacity of the HCN $J = 1$–0 transition can be derived from the line intensity ratios of the $J = 1$–0 hyperfine components. The degeneracies of the HCN $J = 1$, $F = 0,1,2$ states are 1, 3, and 5. If τ_0, τ_1, τ_2 denote the optical depths of the transitions from these three states to the ground state, respectively, we find under conditions of local thermodynamical equilibrium $\tau_1 = 3\tau_0$ and $\tau_2 = 5\tau_0$. The intensity ratios of the hyperfine transitions are then $R_{12} = I(F = 1\text{–}1)/I(F = 2\text{–}1) = (1 - e^{-3\tau_0}) / (1 - e^{-5\tau_0})$ and $R_{02} = I(F = 0\text{–}1)/I(F = 2\text{–}1) = (1 - e^{-\tau_0}) / (1 - e^{-5\tau_0})$. For NGC 4945, τ_0 was estimated from ^{12}C/^{13}C (Henkel et al. 1994a) and the observed line intensity ratio (see Table 1).

[b] For the ^{12}C/^{13}C ratio in N159, see Johansson et al. (1994); for NGC 4945, see Henkel et al. (1994a).

[c] For NGC 4945, lines are too broad to see individual hyperfine components in the HCN line, but the ^{14}N/^{15}N ratio can be estimated by ^{14}N/^{15}N = (H^{13}CN/HC^{15}N) C/^{13}C. This can also be used to confirm the ^{14}N/^{15}N ratio determined in N159HW.

currently understood in terms of primary hydrostatic ^{14}N production in massive low-metallicity stars (see Laird 1985; Timmes, Woosley, & Weaver 1995), while the secondary production of ^{14}N through the CNO cycle is dominating for $Z \gtrsim Z_\odot/100$ (see Timmes et al. 1995; van den Hoek & Groenewegen 1997).

^{15}N is destroyed during hydrostatic hydrogen-burning (e.g., Wannier et al. 1991; El Eid 1994; Langer & Henkel 1995) and is thus thought to be a product of explosive hydrogen nucleosynthesis. It is synthesized in novae as a mostly primary nucleus (e.g., José & Hernanz 1998). However, current models produce insufficient amounts to account for the Galactic ^{15}N abundance (Kovetz & Prialnik 1997). Alternatively, it may be produced in Type II supernovae through neutrino spallation of primary ^{16}O (Woosley & Weaver 1995; Timmes et al. 1995; see also Audouze et al. 1977). A small contribution from Type Ia supernovae is also possible (Clayton et al. 1997; although see Nomoto, Thielemann, & Yokoi 1984). In the first case (novae), there is a time delay between star formation and the occurrence of ^{15}N-enriched ejecta, leading to initially high ^{14}N/^{15}N ratios that gradually decrease with time (for an illustration, see, e.g., Fig. 4 of Güsten & Ungerechts 1985). In the second case (massive stars), rapid injection of ^{15}N into the ISM leads to initially small ^{14}N/^{15}N ratios that gradually increase with time when the ^{14}N contribution from low-mass stars becomes significant.

Analyzing ^{14}N/^{15}N data from HCN and NH$_3$, it soon became obvious that local ISM and Galactic center ^{14}N/^{15}N ratios are moderately and strongly enhanced relative to the solar system value. Assuming that the solar system, the local ISM, and the Galactic center region form a sequence of increasing degree of nuclear processing (the solar system was assumed to reflect the composition of the outer Galaxy at a time almost 5×10^9 yr ago) led to the conclusion that ^{15}N is predominantly arising from massive stellar progenitors (e.g., Audouze et al. 1977; Güsten & Ungerechts 1985). In this case, the more secondary ^{14}N nucleus becomes more abundant relative to ^{15}N with a higher degree of nuclear processing, yielding ^{14}N/^{15}N ratios of 270, 300–400, and 500–1000 in the solar system, the local ISM, and the Galactic center region, respectively.

Two complications led to the present "nitrogen puzzle." First, the Sun is more metal rich than the local ISM (e.g., Russell & Dopita 1992; Cameron 1993; Cunha & Lambert 1994; Meyer 1997), in spite of its age. Second, Dahmen, Wilson, & Matteucci (1995) found a Galactic disk gradient with ^{14}N/^{15}N ratios (from HCN) increasing with Galactocentric distance. The first complication is easily resolved within the framework of primary ^{15}N production, if we note that the Sun is particularly enriched with nuclei processed in massive stars. This leads to enhanced ^{18}O/^{17}O ratios (Henkel & Mauersberger 1993; Henkel et al. 1994b) and to reduced ^{14}N/^{15}N ratios relative to the local ISM. The ^{14}N/^{15}N gradient is a more severe problem. The gradient implies that either the initial mass function (IMF) is biased in favor of high-mass stars in the inner Galactic disk (there is no observational support for such a bias) or that infall of halo gas or of cannibalized dwarf galaxies have altered interstellar abundances. Most galactic ^{14}N/^{15}N values are determined from ^{14}N/^{15}N:^{12}C/^{13}C double isotope ratios. Carbon fractionation may lead to small deviations between HCN/H^{13}CN and ^{12}C/^{13}C abundance ratios (see Langer et al. 1984; Langer & Graedel 1989; Wilson & Matteucci 1992; Wilson & Rood 1994), but this should not alter the sign of a gradient. Assuming instead delayed injection of ^{15}N via novae into the ISM (e.g., Dahmen et al. 1995) fails to account for the large measured ^{14}N/^{15}N ratios in the Galactic center region with its high number of potential nova candidates (see Shafter 1997).

Solving the nitrogen puzzle requires the determination of small (≈100) ^{14}N/^{15}N ratios in a (post-)starburst environment that is strongly influenced by the ejecta from massive stars (Henkel & Mauersberger 1993; Henkel et al. 1994b). Only a lower ^{14}N/^{15}N limit of order 100 was obtained toward M82 (Henkel et al. 1998). Our ^{14}N/^{15}N ratio from NGC 4945 strongly suggests that the bulk of ^{15}N is ejected by massive stars.

The ISM of the LMC is less processed than the solar system and the local ISM and should also be characterized by overabundances of nuclei ejected from massive stars. $[\mathrm{C/O}]_{\mathrm{LMC}} \sim [\mathrm{N/O}]_{\mathrm{LMC}} \sim -0.3$ is consistent with this hypothesis (e.g., Westerlund 1990). Thus, if ^{15}N is released by massive stars, an "overabundance" of ^{15}N relative to ^{14}N is expected; in the LMC, ^{14}N/^{15}N should be significantly smaller than ratios measured in the solar system and the local ISM.

Our observational results from the LMC and NGC 4945 thus provide strong support for ^{15}N *being predominantly ejected by Type II supernovae*. This finding is not consistent with the sign of the Galactic disk ^{14}N/^{15}N gradient (Dahmen et al. 1995). It also seems to be in conflict with numerical calculations of massive star nucleosynthesis (e.g., Weaver & Woosley 1993; Woosley & Weaver 1995). While without the contribution of neutrino-induced nucleosynthesis to the production of ^{15}N, massive stars would destroy rather than produce this isotope (see Weaver & Woosley 1993), Woosley & Weaver (1995) find the neutrino production with the (uncertain) currently predicted neutrino scattering cross sections not sufficient to explain the solar system abundance of ^{15}N (see also Timmes et al. 1995). However, recent massive star models that take the effects of rotation on the stellar structure and nucleosynthesis into account (Heger et al. 1997; Heger, Woosley, & Langer 1999; Langer, Heger, & García-Segura 1998) indicate the possibility of abundant hydrostatic production of ^{15}N in case of mixing between the hydrogen-burning and the helium-burning shell, a mechanism already discussed by Jorissen & Arnould (1989). Consequently, although there are considerable uncertainties and weakly restricted parameters in the rotating massive star models that need to be explored in the near future, massive stars should be considered as an important source of ^{15}N in galaxies, particularly so after the observational facts reported in the present Letter.

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