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Isotopic abundances of carbon and nitrogen in Jupiter-family and Oort Cloud comets[⋆]

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Abstract. The $^{12}C^{14}N/^{12}C^{15}N$ and $^{12}C^{14}N/^{13}C^{14}N$ isotopic ratios are determined for the first time in a Jupiter-family comet, 88P/1981 Q1 Howell, and in the chemically peculiar Oort Cloud comet C/1999 S4 (LINEAR). By comparing these measurements to previous ones derived for six other Oort Cloud comets (including one of Halley-type), we find that both the carbon and nitrogen isotopic ratios are constant within the uncertainties. The mean values are $^{12}C/^{13}C \simeq 90$ and $^{14}N/^{15}N \simeq 145$ for the eight comets. These results strengthen the view that CN radicals originate from refractory organics formed in the protosolar molecular cloud and subsequently incorporated in comets.

Key words. comets: abundances – comets: individual: 88P/Howell – comets: individual: C/1999 S4 (LINEAR)

1. Introduction

Determination of the abundance ratios of the stable isotopes of the light elements in different objects of the Solar System provides important clues in the study of its origin and early history. Comets carry the most valuable information regarding the material in the primitive solar nebula.

The discovery of a number of emission features belonging to the $^{12}C^{15}N$ B-X (0, 0) band ($\lambda \sim 3880$ Å) allowed us to make the first optical measurement of the nitrogen isotopic ratio $^{14}N/^{15}N$ in a comet (Arpigny et al. 2003). This ratio (∼140) was found to be lower by a factor of about two than the terrestrial value (272) and less than half those obtained in Hale-Bopp from millimiter measurements of HCN, a possible main parent of CN (Jewitt et al. 1997; Ziurys et al. 1999). Spectra of the fainter comets 122P/de Vico (period ∼74 yr) and 153P/Ikeya-Zhang (period ∼370 yr) gave similar results (Jehin et al. 2004). We also showed that the isotopic ratios in comets at large heliocentric distances ($r \sim 3$ AU) are identical within the uncertainties to the ratios derived when the comets are closer to the Sun (Manfroid et al. 2005). These measurements are summarized in Table 1. The discrepancy between the nitrogen isotopic ratios derived from CN and HCN would indicate that cometary CN radicals are produced from at least one other source enhanced in ^{15}N, ruling out HCN as the major parent of CN as also suggested by other observations (e.g. Woodney et al. 2004). On the other hand, the optical determinations of the $^{12}C/^{13}C$ ratio consistently yield values around 90, only slightly lower than the HCN millimiter measurements (Table 1), and in agreement with the solar value (89).

As seen in Table 1, the optically determined nitrogen isotopic ratios are remarkably similar. However, all the comets studied so far were long-period or Halley-type comets coming from the Oort Cloud (10^3–10^5 AU from the Sun). Jupiter-family short-period comets constitute a different group thought to originate from the Edgeworth-Kuiper belt (30–10^3 AU from the Sun). According to current paradigm (e.g. Weissman 1999), Jupiter-family comets are believed to have formed in the Edgeworth-Kuiper belt, although it has been argued recently that they could have formed much closer in (Gomes 2003; Levison & Morbidelli 2003). On the other hand, Oort Cloud comets are in fact born in the region of the solar nebula where the giant planets appeared (5–30 AU from the Sun). In any case, since these two categories of comets may have different birthplaces, it is important to know whether their isotopic ratios differ, or not. In the present paper, we discuss the first determination of the carbon and nitrogen isotopic ratios in a bona fide Jupiter-family comet: 88P/1981 Q1 Howell. It has an orbital

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Table 1. Carbon and nitrogen isotopic ratios in comets.

Comet	Type	r (AU)	Method (carrier)	^{12}C/^{13}C	^{14}N/^{15}N	References
C/1995 O1 (Hale-Bopp)	OC	0.92	Millimeter (HCN)	109 ± 22	330 ± 98	Ziurys et al. (1999)
		1.20	Millimeter (HCN)	111 ± 12	323 ± 46	Jewitt et al. (1997)
C/1995 O1 (Hale-Bopp)	OC	0.92	Optical (CN)	90 ± 30	160 ± 40	Manfroid et al. (2005)
		0.93	Optical (CN)	95 ± 40	140 ± 45	Manfroid et al. (2005)
		2.73	Optical (CN)	80 ± 20	140 ± 30	Manfroid et al. (2005)
C/2000 WM1 (LINEAR)	OC	1.21	Optical (CN)	115 ± 20	140 ± 30	Arpigny et al. (2003)
C/2001 Q4 (NEAT)	OC	0.98	Optical (CN)	90 ± 15	135 ± 20	Manfroid et al. (2005)
		3.70	Optical (CN)	70 ± 30	130 ± 40	Manfroid et al. (2005)
C/2003 K4 (LINEAR)	OC	1.20	Optical (CN)	90 ± 15	135 ± 20	Manfroid et al. (2005)
		2.61	Optical (CN)	85 ± 20	150 ± 35	Manfroid et al. (2005)
122P/1995 S1 (de Vico)	HT	0.66	Optical (CN)	90 ± 10	140 ± 20	Jehin et al. (2004)
153P/2002 C1 (Ikeya-Zhang)	OC	0.92	Optical (CN)	90 ± 25	170 ± 50	Jehin et al. (2004)
C/1999 S4 (LINEAR)	OC	0.88	Optical (CN)	100 ± 30	150 ± 40	This work
88P/1981 Q1 (Howell)	JF	1.41	Optical (CN)	90 ± 10	140 ± 15	This work

Comet types: OC: Oort Cloud; HT: Halley-type; JF: Jupiter-family.

period $P = 5.5$ yr and a Tisserand invariant $T_{\mathrm{J}} > 2$ (Fernandez et al. 1999).

Assumed to be formed at distances ranging from 5 to 30 AU from the Sun, Oort Cloud comets may experience a variety of nebular temperatures and densities. Recently, Mumma et al. (2001) found that the chemical composition of comet C/1999 S4 (LINEAR) greatly differs from other Oort Cloud comets (namely Hale-Bopp), suggesting some processing in the hotter Jupiter-Saturn region (and then named "Jovian-class" Oort Cloud comet, not to be confused with Jupiter-family comets). The chemical peculiarity of C/1999 S4 (LINEAR) was further demonstrated by Biver et al. (2002) and Mumma et al. (2003). Comet C/1999 S4 (LINEAR) is also analysed in the current paper, making with 88P/Howell a sample of two comets thought to be formed in very different environments.

2. Observations and data analysis

Observations of comet 88P/Howell were carried out with the Ultraviolet-Visual Echelle Spectrograph (UVES) mounted on the 8.2 m UT2 telescope of the European Southern Observatory Very Large Telescope (ESO VLT). Eleven exposures were secured in service mode during the period April 18, 2004 to May 24, 2004. The total exposure time amounts to 11.1 h. The 0.44 × 8.0 arcsec slit was centered on the nucleus and oriented along the tail, providing a resolving power $R \simeq 80\,000$. The comet heliocentric distance ranges from $r = 1.37$ AU to $r = 1.44$ AU, and its radial velocity from $\dot{r} = 0.89$ km s^{-1} to $\dot{r} = 5.90$ km s^{-1}.

Observations of comet C/1999 S4 (LINEAR) were performed with the 2Dcoudé echelle spectrograph at the 2.7 m Harlan J. Smith telescope of the McDonald Observatory. The resolving power was $R \simeq 60\,000$. The total exposure time of 7.3 h was divided in 16 exposures of 1200 s or 1800 s each, distributed in the period June 25, 2000 to July 17, 2000, i.e. just before the comet's disruption. Heliocentric distances and radial velocities range from $r = 0.97$ AU to $r = 0.78$ AU, and $\dot{r} = -19.6$ km s^{-1} to $\dot{r} = 7.4$ km s^{-1}.

Data reduction and analysis were done as in previous papers. Basically, we compute synthetic fluorescence spectra of the ^{12}C^{14}N, ^{13}C^{14}N and ^{12}C^{15}N $B\,^2\Sigma^+ - X\,^2\Sigma^+$ (0, 0) ultraviolet bands for each observing circumstance. Isotope ratios are then estimated by fitting the observed CN spectra with a linear combination of the synthetic spectra of the three species. For more details we refer to Arpigny et al. (2003), Jehin et al. (2004) and Manfroid et al. (2005). An example is shown in Fig. 1. The derived carbon and nitrogen isotopic ratios are ^{12}C^{14}N/^{13}C^{14}N = 90 ± 10 and ^{12}C^{14}N/^{12}C^{15}N = 140 ± 15 for comet 88P/Howell, and ^{12}C^{14}N/^{13}C^{14}N = 100 ± 30 and ^{12}C^{14}N/^{12}C^{15}N = 150 ± 40 for comet C/1999 S4 (LINEAR). As seen from Table 1, these ratios are identical within the uncertainties to the values we measured for other comets.

3. Discussion

The carbon and nitrogen isotopic ratios derived from CN are similar for all the comets of our sample independently of their types and birthplaces. The mean values are ^{12}C/^{13}C = 90 ± 4 and ^{14}N/^{15}N = 145 ± 4 for the eight comets. This is in remarkable contrast with the strong variability observed among other Solar System bodies (Zinner et al. 1998; Owen et al. 2001). In any case, the value of the nitrogen isotope ratio lies outside the range of measurements in the solar wind (180–500, Kallenbach et al. 2003) and it is inconsistent with the lower limit (>360) derived from the study of lunar soils (Hashizume et al. 2000). It is also quite distinct from the ^{14}N/ ^{15}N ratio (∼450) in the atmosphere of Jupiter, which was proposed as a protosolar value (Owen et al. 2001; Fouchet et al. 2004). We believe that the ratio we measure in cometary CN is not necessarily incompatible with the latter view, but rather suggests the possible (or likely?) coexistence of more than one nitrogen isotope ratio characterizing different components in the protosolar nebula.

Since it is unlikely that all comets originate from an isolated region of the protosolar cloud, the constancy of the ^{14}N/^{15}N ratio suggests that the isotope carrier at the origin of the CN radicals is homegeneously distributed within the protosolar

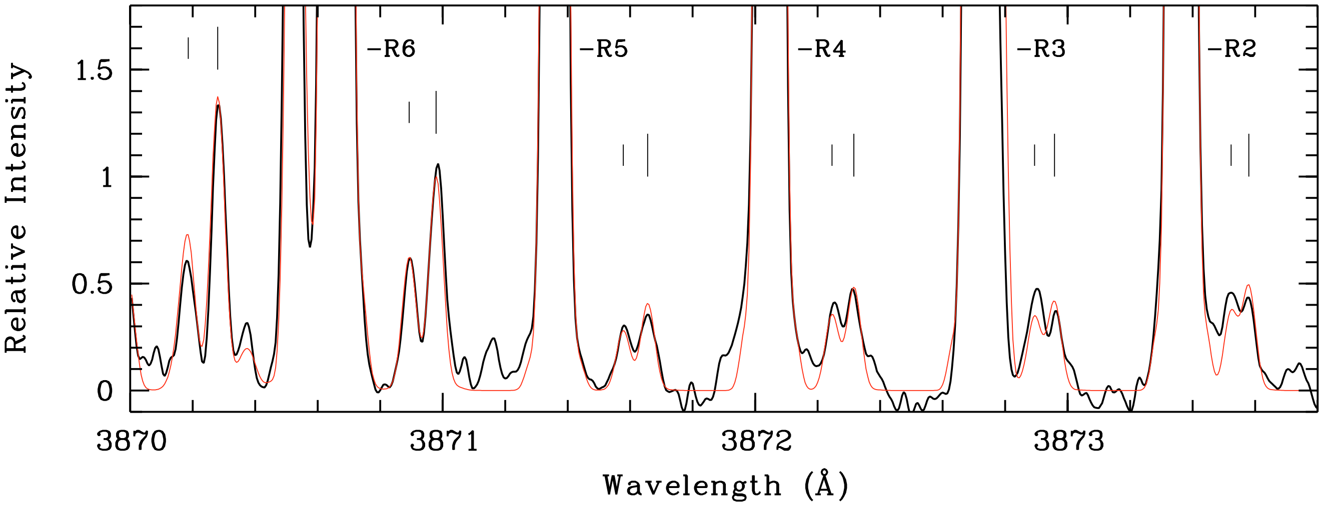

Fig. 1. A section of the spectrum of the CN (0, 0) band in comet 88P/Howell. *Thick line*: observed spectrum; *thin (red) line:* synthetic spectrum of $^{12}C^{14}N$, $^{12}C^{15}N$ and $^{13}C^{14}N$ with the adopted isotopic abundances. The lines of $^{12}C^{15}N$ are identified by the short ticks and those of $^{13}C^{14}N$ by the tall ticks. The quantum numbers of the *R* lines of $^{12}C^{14}N$ are also indicated.

cloud and comes unchanged from it, even in comet C/1999 S4 (LINEAR) which may have experienced high temperatures in the Jupiter-forming region (Mumma et al. 2001). This would require that CN originates from refractory compounds aggregated in the protosolar cloud. In fact, the discrepancy between the nitrogen isotope ratios derived from millimeter HCN and optical CN and the independence of the $^{14}N/^{15}N$ ratio on heliocentric distance has led us (Arpigny et al. 2003; Manfroid et al. 2005) to suggest that the dominant source of CN – the carrier of ^{15}N – could be refractory organics. Good candidates are HCN polymers (Rettig et al. 1992; Kissel et al. 2004; Fray 2004), or grains containing organic macromolecules and reminiscent of "cluster" interplanetary dust particles (IDPs) known to have low $^{14}N/^{15}N$ ratios (Messenger 2000; Aléon et al. 2003; Keller et al. 2004). The hypothesis involving HCN polymers implicitly assumes that their degradation may directly and predominantly produce CN radicals, which is not inconsistent with current experimental limits (Fray 2004, and references therein). Besides, according to Rettig et al. (1992), the physico-chemical properties of HCN polymers indicate that these compounds can likely release CN (and NH_2) radicals by dissociation. The $^{14}N/^{15}N$ ratio measured on HCN in comet Hale-Bopp (∼330) might be the result of a mixture between unprocessed HCN with protosolar value (∼450, in the sense of Owen et al. 2001) and ^{15}N-enriched HCN released from HCN polymers (characterized, as the CN we observe, by $^{14}N/^{15}N$ ∼145).

The difference between the nitrogen isotopic ratios measured for CN and HCN may indicate isotope fractionation in the protosolar cloud. A few mechanisms based on ion-molecule and gas-grain reactions in a cold interstellar medium have been proposed to explain ^{15}N enhancement with respect to the isotope abundance in N_2 which is usually thought to be the major nebular reservoir of nitrogen (Terzieva & Herbst 2000; Rodgers & Charnley 2004). But it is not clear whether such mechanisms can quantitatively reproduce the nitrogen isotopic ratio derived from CN, its uniform distribution throughout the protosolar cloud whatever the fluctuations in temperature and density, and how it can be incorporated into CN-bearing grains. Moreover, the proposed mechanisms seem to be efficient at low temperature (∼10 K, Terzieva & Herbst 2000; Charnley & Rodgers 2002). Kawakita et al. (2005), by considering the very similar spin temperatures measured for various molecules in comets of both Oort Cloud and Jupiter-family types, have recently proposed that the Solar System was born in a warm dense molecular cloud near 30 K rather than a cold dark cloud at 10 K. A higher protosolar temperature was also suggested by Meier & Owen (1999) on the basis of cometary deuterium-to-hydrogen data. More work is therefore needed to assess the reality of fractionation – still very attractive – namely in warmer interstellar clouds. Mass-independent nitrogen fractionation based on selective photo-dissociation may also be worth investigating, as done for example by Yurimoto & Kuramoto (2004) to explain oxygen isotopic anomalies.

On the other hand, the small $^{14}N/^{15}N$ ratio we measure in comets could originate from an external source and, for some reason, be preferentially locked in refractory organics. ^{15}N enhancement may be attributed to a contamination by nucleosynthesis products ejected by nearby massive stars, as observed in the Large Magellanic Cloud and starburst galaxies (Henkel & Mauersberger 1993; Chin et al. 1999; Wang et al. 2004). This would be consistent with a $^{14}N/^{15}N$ ratio smaller than the interstellar medium (ISM) value at the solar circle: $^{14}N/^{15}N \simeq 450 \pm 22$ (Wang et al. 2004). A contamination by massive stars could also slightly increase the $^{12}C/^{13}C$ ratio with respect to $^{12}C/^{13}C \simeq 77 \pm 7$ measured in the local ISM (Henkel & Mauersberger 1993), as observed. Isotopic contamination by massive stars is independently suggested by the study of extinct radionuclides in meteorites (e.g. Cameron et al. 1995). Interestingly enough, the higher temperature of the protosolar cloud proposed by Kawakita et al. (2005) would necessitate the vicinity of sites of formation of massive stars. Massive stars also provide large amount of ultraviolet radiation which may initiate HCN polymerization as suggested by Rettig et al. (1992). If this polymerization (or another, unknown, mechanism) locked up the ^{15}N-enriched nitrogen in a solid phase before it spreads throughout the protosolar cloud, this could explain the nitrogen isotopic differences observed between different molecules in comets and among the various objects and reservoirs in the Solar System (Owen et al. 2001). A similar effect could be expected for the carbon isotopes although much smaller and within the errors bars.

Apart from the need to identify contamination or fractionation processes appropriate to either type of CN progenitors, polymers or organic macromolecules, it will also be very important to measure the ^{14}N/^{15}N ratio in different N-bearing molecules to establish a complete inventory of nitrogen isotopes in comets: HCN (for which a single measurement has been possible so far), NH_3 and/or NH_2 (which is a direct product of ammonia), N_2, C_2N_2 if present. Some variation may be expected depending on the mechanisms of ^{15}N enrichment and the sizes of the various nitrogen reservoirs. A comparison with accurate measurements of the solar-wind isotopes from samples collected by the Genesis space mission should help to distinguish between the possible scenarios.

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