THE NITROGEN AND CARBON ISOTOPIC COMPOSITION OF THE SOLAR NEBULA.
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Summary: We report high-precision measurements of nitrogen and carbon isotopic compositions of a carbon-bearing titanium-nitride (osbornite) in a calcium-aluminum-rich inclusion (CAI) from the CH/CB-like carbonaceous chondrite Isheyevo. The mineralogy and petrography of the CAI and thermodynamic calculations indicate that the osbornite formed by gas-solid condensation in a high-temperature (~2000 K) region of the solar nebula. Because isotopic fractionation at high temperature is small, the measured nitrogen ($^{15}N/^{14}N = (2.356\pm0.018)\times10^{-3}$) and carbon ($^{13}C/^{12}C = 0.01125\pm0.00008$; 1σ) isotopic compositions of the Isheyevo osbornite are representative of the solar nebula and, hence, of the Sun. This conclusion is supported by the observations that (*i*) the measured $^{13}C/^{12}C$ ratio is indistinguishable from the spectroscopic determination of the $^{13}C/^{12}C$ ratio of the solar photosphere and (*ii*) the measured $^{15}N/^{14}N$ ratio of osbornite is in excellent agreement with the Galileo spacecraft measurement of the nitrogen isotopic composition of the Jovian atmosphere, the second largest reservoir of nitrogen in the Solar System. Additionally, the inferred $^{15}N/^{14}N$ ratio of the solar nebula is also similar to the nitrogen isotopic composition of the vast majority of chondritic nanodiamonds, suggesting their solar nebula origin. For a fully referenced text see [1].

Results: A direct laboratory measurement of the nitrogen and carbon isotopic composition of the solar nebula would be possible if a high-temperature, nitrogen- and carbon-bearing condensate was identified in a primitive chondrite. The main candidate for such a phase is titanium nitride (TiN; osbornite), which is predicted to form together with titanium carbide (TiC) by gas-solid condensation from a fractionated nebular gas with enhanced C/O ratios (0.91–0.94). Because there is a solid solution between TiN and TiC, osbornite condensing from the solar nebula gas is expected to contain substantial amounts of carbon. During our systematic studies of the primitive, metal-rich (CH and CB) carbonaceous chondrites, we have discovered an osbornite-bearing CAI in the CH/CB-like meteorite Isheyevo (Fig. 1). Although the host meteorite has experienced mild shock, none of its components show evidence for post-accretionary thermal metamorphism or aqueous alteration. The osbornite-bearing CAI is an irregularly shaped, concentrically zoned object, ~65×100 μm in size. The core of this object consists of polycrystalline osbornite, initially identified based on its very distinct optical properties. At the sensitivity level of the electron microprobe, the osbornite was found to contain no metals other than titanium. The osbornite core contains small platinum-group element inclusions and is surrounded by the layers of grossite ($CaAl_4O_7$), spinel ($MgAl_2O_4$), melilite (gehlenite ($Ca_2Al_2SiO_7$) – åkermanite (Ca_2MgSiO_7) solid solution) and Al-diopside [$(Ca,Mg,Al)(Si,Al)_2O_6$] (Fig. 1).

The mineralogy of the osbornite-bearing CAI is extremely refractory and similar to other CAIs in CH chondrites. The refractory nature, layered textures, volatility-fractionated rare earth element abundance patterns, ^{16}O-rich isotopic compositions and general lack of nuclesynthetic isotopic anomalies in these CAIs are consistent with their early formation by gas-solid condensation. We infer that the Isheyevo CAI, including the osbornite phase, formed in a high-temperature region of the solar nebula where all solids were initially evaporated and the gas homogenized. Under such conditions there is little isotopic fractionation between gas and solids and the nitrogen and carbon isotopic composition of osbornite in the Isheyevo CAI must be representative of the solar nebula.

The nitrogen and carbon isotopic compositions of the osbornite mineral was measured by secondary ion mass-spectrometry (SIMS) using the NanoSIMS N50 ion microprobe at the Muséum National d'Histoire Naturelle in Paris.

Two measurements of different osbornite regions yielded consistent $^{15}N/^{14}N$ ratios of $(2.342\pm0.016)\times10^{-3}$ and $(2.371\pm0.022)\times10^{-3}$ (1σ), respectively, with an average value of $(2.356\pm0.018)\times10^{-3}$. This corresponds to a $\delta^{15}N$ = -359±5‰ relative to the nitrogen isotopic composition of terrestrial air. The measured $^{13}C/^{12}C$ ratios were (0.01129±0.00005) and (0.01121±0.00012) (1σ), respectively, with an average of (0.01125±0.00008), which does not point to a pre-solar origin of the osbornite phase.

Discussion: Figure 2 compares the inferred determination of the $^{15}N/^{14}N$ ratio of the solar nebula to the nitrogen isotopic compositions for the interstellar medium, solar wind, planetary atmospheres, meteorites and comets. Meteorites and micrometeorites are characterized by high $^{15}N/^{14}N$ ratios relative to the solar nebula; isotopic hotspots in micrometeorites and in insoluble organic material from primitive carbonaceous chondrites show extreme $^{15}N/^{14}N$ ratios up to

15×10^{-3}. From astronomical observations of Oort-cloud, Halley-type and Jupiter family comets, two characteristic nitrogen isotopic compositions have been obtained. *i*) CN-radicals generally have high $^{15}N/^{14}N$ ratios, in the range from 6×10^{-3} to 8×10^{-3} and *ii*) HCN molecules released by Hale-Bopp had $^{15}N/^{14}N$ ratios between the solar nebula value and the terrestrial atmosphere. These data show that solids from small solar system bodies are systematically enriched in ^{15}N relative to the inferred solar nebula value. An important exception are nanodiamonds, which occur in abundances up to 0.1% in chondritic meteorites and are characterized by $^{15}N/^{14}N$ ratios $\sim2.39\times10^{-3}$ and $^{13}C/^{12}C$ ratios similar to the solar nebula value. There is therefore no *a priori* reason to assume that nanodiamonds formed around an exploding supernova. On the contrary, their nitrogen and carbon isotopic compositions are broadly consistent with a solar nebula origin.

The Galileo spacecraft measurement of the nitrogen isotopic composition of the Jovian atmosphere, $^{15}N/^{14}N = (2.3\pm0.3)\times10^{-3}$ (3σ), is very similar to the inferred solar nebula value. This supports the suggestion that nitrogen in the Jovian atmosphere is derived primarily from the solar nebula. However, our measurement is more than one order of magnitude more precise than that from the Galileo spacecraft, and thus provides a much better constraint on the solar nebula. When the $^{15}N/^{14}N$ ratio of the Jovian atmosphere becomes known to higher precision, these two numbers in combination will allow different formation models for Jupiter to be critically evaluated. For the moment, the excellent match in nitrogen isotopic compositions between the solar nebula and the Jovian atmosphere (Fig. 2), and the observation of nearly identical enrichment factors for N, Ar, Kr, Xe, C, O and S (relative to solar) in the Jovian atmosphere, appears to be inconsistent with a significant contribution to Jupiter from known comets.

The solar wind is accelerated in at least three regimes that might have different elemental abundances and different isotopic compositions. However, the isotopic composition of the solar wind, including the $^{15}N/^{14}N$ ratio, is poorly known. This hinders a better understanding of important physical processes in the Sun. Measurements by the SOHO spacecraft have yielded a ratio of $(3.8\pm1.8)\times10^{-3}$. Isotopic measurements of nitrogen implanted into lunar soils show great variability and have fueled a long-lasting debate about the nature of the solar wind. Correlated measurements of $^{15}N/^{14}N$ and D/H ratios in material trapped in lunar soil particles have recently indicated an upper limit on the solar wind $^{15}N/^{14}N$ ratio. The solar wind contains essentially no deuterium and by extrapolation of the measured $^{15}N/^{14}N$ ratios to zero deuterium abundance the solar wind $^{15}N/^{14}N$ ratio was constrained to be $<2.8\times10^{-3}$. This result is consistent with the inferred solar nebula value and argues against the presence of 'anomalous' nitrogen in lunar soils.

The major scientific objective for the Genesis sample return mission is to characterize precisely the elemental abundances and isotopic compositions of the solar wind. Together with the anticipated measurements from the Genesis mission, our precise determination of the solar nebula $^{15}N/^{14}N$ ratio will enable a detailed understanding of the nitrogen isotopic composition of the solar wind and provide a solid basis for measurements of its long-term isotopic variations. This will shed light on the relationship between the solar wind and its source, the outer convection zone, which is essential in order to improve solar physics models for processes such as e.g. gravitational settling.

Reference: [1] Meibom et al. (2007) ApJL, in press.

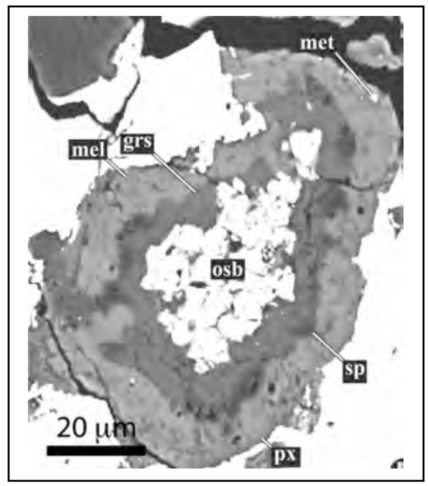

Figure 1. Isheyevo CAI with osbornite core. grs = grossite; mel = melilite; met = PGE-bearing metal; osb = osbornite; px = Al-diopside; sp = spinel.

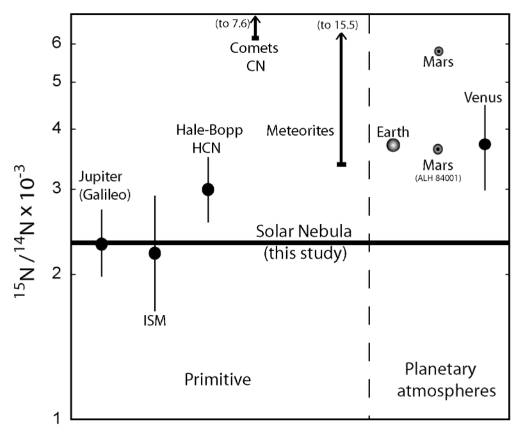

Figure 2: Measurements of $^{15}N/^{14}N$ in primitive and evolved (planetary atmosphere) reservoirs in the solar system. The error-bars associated with the solar nebula value from this study are comparable to the width of the horizontal line.