Coordinated In-Situ Analysis of Meteoritic Nanodiamonds

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Introduction

Meteoritic nanodiamonds (NDs)

- carbon nanograins (2–5 nm) trapped in carbonaceous meteorites thought to be presolar
- carry stellar nucleosynthetic anomalies and encode processes predating the Solar System.

Challenge

Traditional bulk analyses mask ND subpopulation variation, preventing origin(s) identification.

Objective

Differentiate **presolar stardust** vs. **solar system** ND formation in carbonaceous chondrites and returned asteroid samples

Methods

Sulfur -embed Matrix, Microtome → **Sample Prep** → 70-100 nm thin section

In-situ aberration corrected STEM/TEM → **Imaging** → EDXS (composition) EELS (bonding)

NanoSIMS → **Isotopic Imaging** → C,N Isotopes

Technical Approach

Locate ND clusters embedded in organic matter in carbonaceous chondrites and returned asteroid samples

Measure C and N isotopes of clusters to check for multiple formation histories

Initial STEM-EDXS-EELS Results

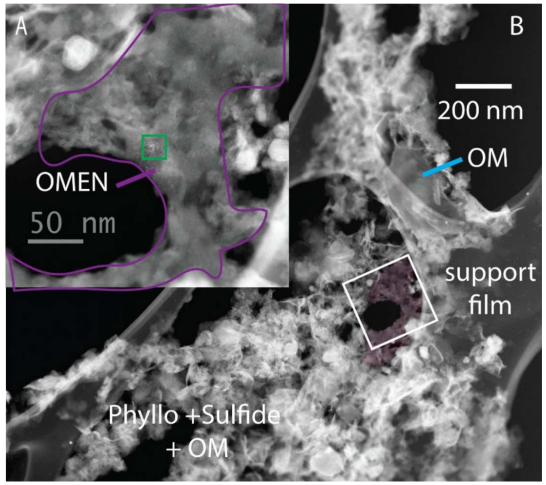


Figure 1 (left) STEM HAADF of microtomed Ryugu particle on lacey carbon grid.

(A) Organic matter (OM) with embedded nanodiamonds (OMEN) (magenta)

(B) Petrographic context OMEN in fine grained matrix (phyllosilicates/ sulfides/diamond-free OM). Elliptical void in OMEN suggests **NDs form as an interstellar icy particle rind.**

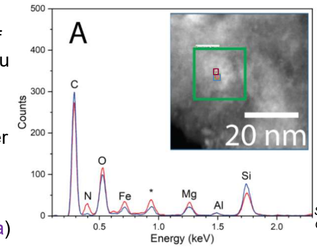
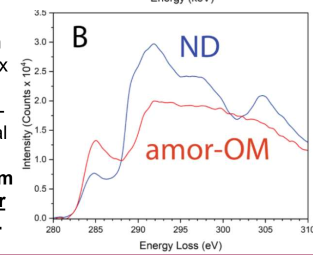


Figure 2
(A) Spectrum image ROI (inset) and Extracted EDXS spectra from Amorphous C **red** is N-richer than ND (**blue**).

Cu peak = system artifact; Si/Al/Mg/Fe/O from heteroatoms in OM; residual from acid dissolution.



(B) Extracted EELS C K-edge From ND (sp³) amor-OM (sp²)

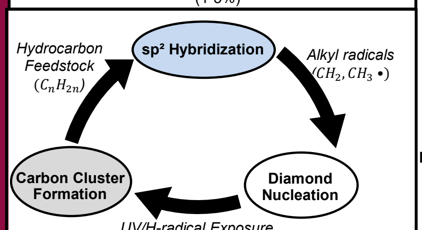
Potential Formation Mechanisms & Distinct Isotopic Fingerprints

UV Photolysis of Organic-Rich Ices

$G_0 > 30$

$$H_2O:CO:CH_4\text{ice} + h\nu(< 200nm) \xrightarrow[k_1]{\text{UV}} [\text{R}]\ (CH_3, CH_2\,\bullet)$$

Organic ice mantles absorb FUV photons (λ < 200 nm)
T < 100 °K
H_2O-rich ice + minor CH_4, CH_3OH, CO, NH_3 (1-5%)



High Flux UV Cavitation in Organic-Rich Ice

$$H_2O:CO:CH_4\text{ice} \xrightarrow[k_1]{\text{plasma/UV}} n(\text{C−based radicals})\cdot + \text{OH} + H_2$$

$$n\,(\text{C−based radicals})\,\bullet \xrightarrow[k_2]{\text{association}} H\text{−terminated}\ [C_\text{n}H_\text{m}]^*$$

$$n\,(\text{C−based radicals}) = (CH_3\text{OH},\ C_2H_5\text{OH}, \ldots)$$

Microplasma T << 100 °K
Residence time ≈1 ms

Diffuse ISM & Cold Molecular Cloud

Photon-processed ice grains

UV Flux **FUV Flux (912-1700Å)** Variable UV

Outer Nebula

cluster-mediated CO–H_2 ice reactions

UV Flux **FUV Flux (912-1700Å)** Variable UV

Circumstellar Outflow

Early Solar System active accretion
Lyα Dominated (88%)

UV Flux **FUV Flux (912-1700Å)** **High UV**

Inner Nebula

Hydrocarbon Catalysis on Fe-Ni grains under solar nebula conditions

UV Flux **FUV Flux (912-1700Å)** **High UV**

Isotopic Signature ⇌ Origin

Isotopic Signature ⇌ Origin
Initial Composition of Organic Precursors
Fractionation due to thermal, photolytic, or ion-molecule reaction

Hot Formation Mechanisms

Direct vapor condensation in C-star environments & type II Supernovae

Precursor Flash Heating/Collisional Shock

$$\text{C}_\text{org} \xrightarrow[k_1]{\text{flash heating/shock}} \text{C (v)}$$

Carbon Vapor Supersaturation

$$\text{C (v)} \xrightarrow[k_2]{\text{supersaturation}} [\text{C}_n]^*$$

Shockwave accelerated Grain-Grain Collisions in the ISM

Shock IC (P ~ 10 GPa) (T ≫ 1000 K)

Shock Compression $\text{C}_\text{org} \xrightarrow[\text{high P, T (shock)}]{k_1} [\text{C}_\text{org}]^*$

Bond Reorganization & Rapid Quench $[\text{C}_\text{org}]^* \xrightarrow[k_2]{\text{rapid quench}} \text{C}_\text{diamond nucleus}$

Co-Formation of Glassy Carbon $[\text{C}_\text{org}]^* \rightarrow \text{C}_\text{glassy}\quad (k_3)$

Fischer-Tropsch Fe-Ni Catalysis

M = Fe-Ni catalytic site (metal grain surface)
Nebular conditions (~300-700K, 10^{-4} atm)

CO adsorption and activation

$$\text{CO(g)} + M \overset{k_1}{\rightarrow} M - C\ +\ M - O$$

H_2 activation

$$\text{H}_2\text{(ads)} + 2\,M \overset{k_H}{\rightarrow} 2\,M - H$$

CH_2 initiation

$$M - C + 2\,M - H \overset{k_\alpha}{\rightarrow} M - CH_2 + M$$

Carbene insertion

$$M - CH_2 + \text{CO(g)} + M - H \overset{k_\text{ins}}{\rightarrow} M - C_2H_4 + M - O$$

Chain growth
repeat CH_2 initiation + Carbene insertion
build M − C_nH_{2n}

References

1. S. J. Desch and N. Miret-Roig, "The Sun's birth environment: Context for meteoritics," Space Sci. Rev., vol. 220, no. 7, Art. no. 76, 2024.
2. G. R. Huss and R. J. Lewis, "Presolar diamond, SiC, and graphite in meteorites," Geochim. Cosmochim. Acta, vol. 60, pp. 331–346, 1996.
3. G. R. Huss, S. T. Husa, and S. A. Sandford, "UV processing of presolar organic ices," Astrophys. J., vol. 849, p. 75, 2017.
4. A. Kouchi et al., "Novel routes for diamond formation in interstellar ices and meteoritic parent bodies," Astrophys. J. Lett., vol. 626, L129, 2005.
5. A. Kumar et al., "Formation of nanodiamonds at near-ambient conditions via microplasma dissociation of ethanol vapour," Nat. Commun., vol. 4, Art. no. 2618, 2013.
6. J. Llorca and I. Casanova, "CO + H_2 reaction over Fe–Ni metal at low pressures: Implications for nebular diamond formation," Geochim. Cosmochim. Acta, vol. 64, no. 15, pp. 2673–2684, 2000.
7. L. R. Nittler and F. Ciesla, "Astrophysics with extraterrestrial materials," *Annu. Rev. Astron. Astrophys.*, vol. 54, pp. 53–93, 2016.
8. G. Pareras et al., "Single-atom catalysis in space – II. Ketene–acetaldehyde–ethanol and methane synthesis via Fischer–Tropsch chain growth," Astron. Astrophys., vol. 687, p. A230, 2024.
9. R. M. Stroud et al., "Electron microscopy observations of the diversity of Ryugu organic matter and its relationship to minerals at the micro-to nano-scale," Meteori. & Planeta. Sci. 59 (8), 2023-2043