Ecology & Evolution | Nov 3, 2026 | 5 min read | By Bryan White

All Five Canonical DNA and RNA Nucleobases Confirmed in Pristine 4.5-Billion-Year-Old Asteroid Samples

Astrobiology * Planetary Science * Prebiotic Chemistry

High-resolution mass spectrometry of pristine regolith returned from the 4.5-billion-year-old carbonaceous asteroids (101955) Bennu and (162173) Ryugu has confirmed the simultaneous presence of all five canonical nucleobases required to encode genetic information in terrestrial life: the purines adenine (A) and guanine (G) , and the pyrimidines cytosine (C) , thymine (T) , and uracil (U) [1, 2, 3] . Analyzed under ultraclean nitrogen-purged curation conditions without exposure to Earth's biosphere, the returned samples from NASA's OSIRIS-REx mission (121.6 grams collected from Bennu's Nightingale crater) alongside JAXA's Hayabusa2 regolith and ultra-low- temperature extractions of carbonaceous chondrites demonstrate that the complete heterocyclic alphabet of DNA and RNA -- together with 14 of the 20 standard proteinogenic amino acids and ancient sodium-carbonate evaporite salts -- formed abiotically inside early Solar System parent bodies [1, 2] .

1. Closing the Terrestrial Contamination Loophole in Meteoritic Prebiotic Chemistry

For more than half a century, planetary geochemists analyzing carbon-rich meteorites (such as the 1969 Murchison CM2 chondrite, the 1950 Murray chondrite, and the 2000 Tagish Lake fall) repeatedly detected purines (adenine, guanine, hypoxanthine, and xanthine) and uracil, yet struggled to verify the unstable pyrimidines cytosine and thymine [3] . Two fundamental analytical barriers stood in the way. First, any meteorite that lands on Earth is immediately exposed to soil microbes, groundwater , and atmospheric moisture, making it difficult to prove that trace parts-per-billion (ppb) levels of canonical nucleobases are truly indigenous rather than terrestrial biological contaminants. Second, traditional laboratory extraction protocols relied on hot formic acid or hydrochloric acid hydrolysis (100-110 deg C), which aggressively deaminates cytosine into uracil (C + H 2 O -> U + NH 3) and degrades fragile pyrimidine ring isomers before chromatographic separation [3] .

The convergence of cold-water ultrasonic extraction coupled to high-performance liquid chromatography with orbitrap high-resolution mass spectrometry (HPLC-ESI-HRMS) [3, 4] and direct spacecraft sample return from asteroids Bennu and Ryugu resolved both problems simultaneously [1, 2] . Because OSIRIS-REx hermetically sealed Bennu's regolith in vacuum and delivered the Sample Return Capsule to cleanroom nitrogen gloveboxes at NASA's Johnson Space Center, the samples never contacted terrestrial water or soil. Furthermore, the indigenous organic matter in Bennu exhibits strongly positive isotopic fractionations in deuterium (deltaD) and heavy nitrogen (delta 15 N ~ +180‰ to +300‰), coupled with an equal (1:1 racemic) mixture of left-handed (L) and right-handed (D) chiral amino-acid enantiomers -- confirming an unmistakable extraterrestrial, non-biological origin [1] .

| Prebiotic Compound Class | | Canonical & Structural Species Detected | | Typical Concentration Range (ppb) | | Abiotic Synthesis & Parent-Body Pathway | | Primary Analytical Verification |

| Purine Nucleobases | | Adenine (A), Guanine (G), Hypoxanthine, Xanthine, Purine | | 5 - 180 ppb | | HCN pentamerization (5 HCN -> C 5 H 5 N 5) & formamide condensation | | Cold-water HPLC-Orbitrap HRMS (Oba et al.; Glavin et al.) [1, 3] |

| Pyrimidine Nucleobases | | Cytosine (C), Uracil (U), Thymine (T), Isocytosine, Imidazole-4-carboxylic acid | | 1 - 45 ppb | | Cyanoacetylene (HC 3 N) + cyanate/urea addition in ammoniated brines; UV ice photolysis | | Mild aqueous extraction avoiding hot-acid deamination [1, 3, 4] |

| Cofactor & Vitamin Precursors | | Nicotinic acid (Vitamin B3 / Niacin), Nicotinamide | | 15 - 110 ppb | | Pyridine carboxylic acid synthesis via aldehyde-ammonia-cyanoacetaldehyde condensations | | Detected in Ryugu (A0106/C0107) and Bennu soluble organic extracts [1, 4] |

| Proteinogenic Amino Acids | | 14 of 20 standard amino acids (Gly, Ala, Asp, Glu, Ser, Thr, Val, Leu, Ile, Pro, etc.) + beta-Ala, AIB | | 1,000 - 70,000 ppb (Total ~70 ppm in Bennu) | | Strecker-cyanohydrin & Michael addition in low-temperature NH 3 -rich aqueous fluids | | Racemic L ~ D enantiomeric ratios & delta 15 N enrichment [1] |

| Evaporite Brine Minerals | | Trona, Gaylussite, Calcite, Halite, Sylvite, Magnesium-Sodium Phosphates | | Major accessory mineral veins | | Late-stage evaporation of alkaline (pH 9-10) carbonated brines inside parent asteroid | | SEM-EDS & X-ray diffraction of Bennu lithologies (McCoy et al.) [2] |

2. Photochemical Ice Processing Followed by Low-Temperature Parent-Body Brine Chemistry

How did a small, airless rubble-pile asteroid synthesize all five canonical nucleobases alongside dozens of structural isomers? Isotopic and mineralogical evidence from Glavin et al. (2025) [1] and McCoy et al. (2025) [2] points to a two-stage chemical reactor operating across the birth of the Solar System:

* Stage 1 -- Interstellar and Outer-Protoplanetary-Disk UV Photochemistry (10-50 K): In the cold outer regions of the solar nebula beyond the ammonia and carbon dioxide snow lines, icy mantles coating silicate dust grains -- composed of H 2 O, CH 3 OH (methanol), NH 3 (ammonia), CO, and HCN -- were irradiated by stellar ultraviolet photons and cosmic rays. Laboratory astrochemistry simulations show that UV photolysis of these simple ices generates reactive radical intermediates that recombine upon warming into a diverse suite of purines, pyrimidines, and structural isomers [3] .

* Stage 2 -- Alkaline Evaporite Brines Inside the Accreted Parent Asteroid (20-80 deg C): Roughly 4.5 billion years ago, those ice-coated grains accreted into Bennu's ~100-kilometer-wide parent planetesimal. Decay of short-lived radionuclides -- primarily aluminum -26 (26 Al, half-life 7.17 x 10 5 years) -- melted the internal ice into an underground network of liquid water brines. Crucially, Bennu's soluble organic extracts contain extraordinarily high concentrations of free ammonia (NH 3 ~ 1,100 ppm, roughly 75x higher than in the Murchison meteorite) [1] , while McCoy et

al. (2025) discovered a complete sequence of evaporite minerals -- including hydrated sodium carbonates (trona and gaylussite), halite, sylvite, and water-soluble magnesium -sodium phosphates [2] .

3. Why Alkaline Phosphate-Rich Brines Stabilized Cytosine and Thymine

The discovery of alkaline sodium-carbonate and phosphate evaporites alongside high ammonia concentrations in Bennu [1, 2] provides the missing chemical mechanism explaining how all five nucleobases survived inside the asteroid. In neutral or acidic water at elevated temperatures, cytosine rapidly hydrolyzes into uracil, and hydrogen cyanide (HCN) volatilizes before it can polymerize into adenine . However, inside Bennu's parent body, evaporitic concentration created cool, alkaline (pH 9-10), ammonia-rich brines:

* Purine Assembly via HCN Pentamerization: High dissolved NH 3 and CN − concentrations drive the classic Oró synthesis (5 HCN -> Adenine) and formamide/cyanogen condensations yielding guanine, hypoxanthine, and xanthine at low temperatures without thermal destruction [1] .

* Pyrimidine Protection & Methylation: In ammoniated carbonate brines, cyanoacetylene (HC 3 N) reacts with cyanate (OCN −) or urea to yield cytosine, while high dissolved ammonia shifts the deamination equilibrium to slow cytosine loss. Simultaneously, formaldehyde (HCHO) and formate serve as C1 methylating agents that convert uracil into 5-methyluracil (thymine) on catalytic phyllosilicate clay and magnetite surfaces [2, 3] .

* Co-Localization with Reactive Phosphates: Even more remarkably, the Bennu samples contain abundant magnesium-sodium phosphate minerals (MgNaPO 4) that are far more water-soluble and chemically reactive than the insoluble calcium apatite (Ca 5 (PO 4) 3 (OH)) typical of terrestrial rocks -- placing all five nucleobases, ribose-forming formaldehyde, and soluble phosphorylation reagents inside the exact same evaporating brine pockets [2] .

4. Implications for Prebiotic Delivery to Hadean Earth and Enceladus

While the presence of all five nucleobases and 14 proteinogenic amino acids in Bennu and Ryugu does not indicate past biology on these asteroids -- as confirmed by the racemic (50% L : 50% D) amino-acid distributions and the accompanying soup of non-biological structural isomers such as isocytosine, beta-alanine, and alpha-aminoisobutyric acid [1] -- it demonstrates that early Earth did not need to synthesize its genetic building blocks entirely from scratch. During the late accretion epoch (4.4-3.9 billion years ago), carbonaceous asteroids and micrometeorites continuously seeded Hadean terrestrial ponds and hydrothermal fields with pre-formed purines, pyrimidines, nicotinic acid (NAD + cofactor precursors) [4] , and reactive phosphate salts. Furthermore, because the evaporite brine mineral assemblage discovered in Bennu closely mirrors the alkaline sodium-carbonate plumes erupting today from Saturn's icy moon Enceladus and the subsurface crust of dwarf planet Ceres [2] , these results suggest that the chemical precursors of RNA and DNA are synthesized wherever ammonia-bearing ices interact with silicate rock across the outer Solar System.

References & Primary Sources

* [1] Glavin, D. P., Dworkin, J. P., Alexander, C. M. O'D., Aponte, J. C., et al. (2025). Abundant ammonia and nitrogen-rich soluble organic matter in samples from asteroid (101955) Bennu. Nature Astronomy 9, 199-210. -- https://doi.org/10.1038/s41550-024-02472-9

* [2] McCoy, T. J., Russell, S. S., Zega, T. J., Thomas-Keprta, K. L., et al. (2025). An evaporite sequence from ancient brine recorded in Bennu samples. Nature 637, 1072-1077. -- https://doi.org/10.1038/s41586-024-08495-6

* [3] Oba, Y., Takano, Y., Furukawa, Y., Koga, T., Glavin, D. P., Dworkin, J. P. & Naraoka, H. (2022). Identifying the wide diversity of extraterrestrial purine and pyrimidine nucleobases in carbonaceous meteorites. Nature Communications 13, 2008. -- https://doi.org/10.1038/s41467-022-29612-x

* [4] Oba, Y., Koga, T., Takano, Y., Ogawa, N. O., Ohkouchi, N., Sasaki, K., et al. (2023). Uracil in the carbonaceous asteroid (162173) Ryugu. Nature Communications 14, 1292. -- https://doi.org/10.1038/s41467-023-36904-3