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REVIEW

A Comprehensive Review of Organic Matter Found in Asteroids (162173) Ryugu and (101955) Bennu

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ABSTRACT

Near-Earth Asteroids (NEAs) are among the planetary bodies that have encountered, and will continue to encounter, our planet. This interaction has provided insights into the composition and origins of asteroids and their relationship to meteorites and other solar system materials. Sample return missions, notably JAXA's Hayabusa2 to Asteroid (162173) Ryugu in 2018 and NASA's OSIRIS-REx to Asteroid (101955) Bennu in 2020, have provided unprecedented access to primitive carbonaceous asteroid material for laboratory analysis. Unlike meteorites, which experience thermal degradation and contamination during atmospheric entry, hermetically sealed asteroid samples preserve a more accurate record of their original chemical state. Analysis of Ryugu samples yielded approximately 20,000 soluble organic compounds, fifteen amino acids including both proteinogenic and non-proteinogenic varieties, and the nucleobase uracil, with subsequent analysis confirming all five canonical nucleobases. These compounds are characteristic of Ivuna-type carbonaceous chondrites, a rare class of meteorites whose bulk elemental abundances approximate solar photospheric composition. The detection of presolar grains in Ryugu samples further indicates the preservation of material predating the formation of our solar system. Bennu samples have corroborated and extended these findings, confirming bio-essential sugars including ribose and phosphate-bearing compounds in addition to containing all five nucleobases, meaning Bennu samples contain representatives of two of the three main structural components of an RNA nucleotide. While the formation pathways and prebiotic significance of these compounds remain subjects of active investigation, these findings prompt broader questions about the relationship between primitive carbonaceous bodies and the molecular history of our solar system.

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1. Introduction

It is estimated that trillions of objects orbit the sun, including planets, meteoroids, comets, and asteroids [1]. Among these, asteroids are one of the most chemically diverse groups that preserve records of early solar system materials, with compositions ranging from iron-rich bodies to volatile carbonaceous types. Carbonaceous near-Earth asteroids are of particular interest because their primitive compositions can inform how planets were created and provide insights into the formation of the volatile and organic compounds found on these non-planetary bodies [2,3]. One such object is Asteroid (162173) Ryugu. In June 2018, the Hayabusa2 spacecraft, operated by the Japanese Aerospace Exploration Agency (JAXA), arrived at Ryugu and deployed two rovers and the MASCOT lander to its surface [2]. This was the second successful asteroid sample-return mission, following the first Hayabusa mission to Asteroid (25143) Itokawa. Hayabusa2 collected three samples from Ryugu, which were hermetically sealed to limit contamination from Earth's atmosphere [3–5].

Asteroid (162173) Ryugu is classified as an Apollo Class Near-Earth Asteroid (NEA), meaning it has a semi-major axis $a > 1.0$ AU and a perihelion distance $q < 1.017$ AU [6]. Its semi-major axis is approximately 1.1896 AU, with one AU being exactly 149,597,870,700 m, approximately the distance between the Earth and the Sun [7–9]. At 1.18 AU, Ryugu possesses an orbit slightly larger than Earth's in characteristic size, and one that can intersect Earth's orbital path. Ryugu is also classified as a Potentially Hazardous Asteroid (PHA) under NASA criteria, which define PHAs as having an Earth minimum orbit intersection distance (MOID) ≤ 0.05 AU and an absolute magnitude $H \leq 22.0$, placing it among objects tracked closely for impact-risk monitoring [6]. This intersection with Earth's orbit suggests that it could have interacted with Earth in the past or has the potential to do so in the future, either through direct collision or through the production of meteoritic debris [2,6]. Recent asteroid sample-return missions, notably JAXA's Hayabusa2 to Ryugu and NASA's OSIRIS-REx to Asteroid (101955) Bennu, have provided us access to asteroid materials for detailed laboratory analysis [10]. Bennu, like Ryugu, is classified as an Apollo Class NEA and PHA, with a semi-major axis of approximately 1.126 AU and a documented probability of Earth impact in the late 22nd century [6,10]. Both asteroids are carbonaceous in composition, and both missions employed hermetic sealing protocols to minimize terrestrial contamination of returned samples, a necessary consideration given that labile organic molecules such as amino acids and nucleobases are among the most susceptible to thermal degradation during atmospheric entry and to contamination from terrestrial sources [4,11,12]. Early analysis of Bennu samples has revealed nucleobases, amino acids, and sugars, extending the organic inventory confirmed in Ryugu and suggesting that such compounds may be a widespread feature of primitive carbonaceous asteroids rather than an anomaly unique to a single body [10,13].

Because of their proximity to Earth and carbonaceous nature, these asteroids offer a valuable opportunity to study the composition and alteration history of primitive carbonaceous bodies and their connection to Earth's early chemical environment [14]. Understanding the organic and elemental compositions of NEAs, such as Ryugu and Bennu, informs our knowledge of chemical processes in the early solar system and their potential influence on Earth [5,10,15].

2. Near-Earth Asteroid Mission Overviews

2.1. Mission Design and Timelines

JAXA's Hayabusa2 collected 5.424 ± 0.217 g of material from two surface locations on Asteroid (162173) Ryugu: the equatorial ridge (sample A0106) and a subsurface site excavated by the Small Carry-on Impactor (sample C0107), the latter providing access to material shielded from long-term space weathering[4,5,16]. Hayabusa2 improved upon its predecessor, the first Hayabusa mission to Asteroid (25143) Itokawa, with a more robust sampling mechanism and the addition of the MASCOT lander for independent surface characterization[2,17]. NASA's OSIRIS-REx mission collected an estimated 121.6 g of surface material from Asteroid (101955) Bennu in October 2020, which is approximately twenty-two times the mass returned by Hayabusa2[18]. Bennu is classified as a B-type asteroid, a subgroup of carbonaceous asteroids distinguished by their low albedo, or ability to reflect incident light, and their relatively featureless reflectance spectra in the visible and near-infrared range[19]. Like Ryugu, Bennu is classified as a Potentially Hazardous Asteroid, with a well-documented probability of Earth impact in the late 22nd century, making it one of the most closely monitored near-Earth objects in NASA's catalog[20]. This substantially larger sample mass from Bennu has enabled a broader range of organic analyses than was possible with Ryugu material, and may account in part for the more extensive organic inventory currently confirmed in Bennu samples relative to Ryugu.

2.2. Significance of Parallel Missions

The near-simultaneous execution of two independent asteroid sample-return missions targeting carbonaceous near-Earth asteroids, one by JAXA, one by NASA, was not coordinated by design, yet it produced a natural scientific experiment. Asteroid (101955) Bennu, the target of NASA's OSIRIS-REx mission, shares broad compositional and orbital characteristics with Asteroid (162173) Ryugu while differing in spectral classification, returned sample mass, and specific organic inventory[21]. Prior to the returns of Hayabusa2 and OSIRIS-REx samples, the study of primitive carbonaceous material was largely confined to meteorite analysis[22]. However, these samples had survived atmospheric entry and suffered varying degrees of terrestrial contamination. The Ryugu and Bennu sample sets collectively represent the first opportunity to study carbonaceous asteroid chemistry in its near-pristine state across two independent bodies, effectively doubling the available reference points for models of early solar system organic chemistry. The analytical advantages of sample return over in-situ spacecraft instrumentation extend beyond sample mass. Laboratory-based analysis allows researchers to apply techniques that cannot be miniaturized for spacecraft deployment, enabling a depth and range of organic characterization that onboard instruments cannot replicate[12].

However, a persistent challenge across all sample return missions is the distinction between intrinsic extraterrestrial organic matter and terrestrial contamination introduced during sample handling, curation, or analysis. Chan et al.[12] identified organic contamination as a fundamental challenge across all sample return missions, stating that terrestrial organic contamination cannot be completely eliminated regardless of the protocols employed. The detection of identical organic compound classes across two independently returned sample sets, processed by different agencies using different protocols, therefore provides a stronger basis for concluding extraterrestrial origin than either dataset could provide alone[12]. This comparative framework will only grow in significance as additional sample analyses are published and as future missions extend the catalog of returned extraterrestrial materials.

3. The Composition and Organic Content of Asteroid Samples

3.1. Organic Compounds and Nucleobase Detection in Ryugu Samples

A comprehensive study by Naraoka et al.[3] of the Ryugu samples detected approximately 20,000 soluble organic compounds and fifteen amino acids in sample A0106 alone[23]. Of the fifteen amino acids detected in sample A0106, both proteinogenic and non-proteinogenic varieties were identified[3,24]. The origin of these compounds appears to be multifaceted. While some may have formed through weathering of Ryugu's parent body (the larger celestial body it originated from), Potiszil et al.[24] propose that at least a portion were synthesized in interstellar space or the early solar nebula through chemical reactions in irradiated ice, and were subsequently incorporated into the asteroid as it formed in the outer solar system[25]. This conclusion is supported by Ryugu's chromium and calcium isotopic compositions, which indicate an origin in the outer regions of the early solar system where such compounds would have been present [24]. On Earth, proteinogenic amino acids represent only twenty of the hundreds of chemically possible amino acids, yet they constitute the vast majority of amino acids found in living organisms. The amino acid inventory of Ryugu, spanning both proteinogenic and non-proteinogenic varieties with potential interstellar origins, therefore reflects a much higher proportion of non-proteinogenic compounds than is found in living organisms on Earth [24,26]. While the presence of both proteinogenic and non-proteinogenic varieties is more consistent with abiotic synthesis than with terrestrial biological contamination, the relative contributions of interstellar synthesis and other synthesis reactions to the final amino acid inventory remain unresolved, highlighting the need for continued isotopic and molecular analysis as additional Ryugu material is evaluated [24,26].

These amino acids provide additional insight when examining the presence of specific identities. The ratio of glycine to β-alanine is a useful metric for abiotic synthesis, as biological systems produce greater quantities of α-amino acids like glycine than β-amino acids like β-alanine. As seen in **Figure 1**, the ratio in samples A0106 and C0107 were found to be 1.76 and 0.96, respectively [24]. Ratios at or near 1 indicate a relatively elevated β-alanine abundance compared to what is typical in biological systems, suggesting abiotic synthesis as a plausible origin for at least a portion of these compounds [27,28].

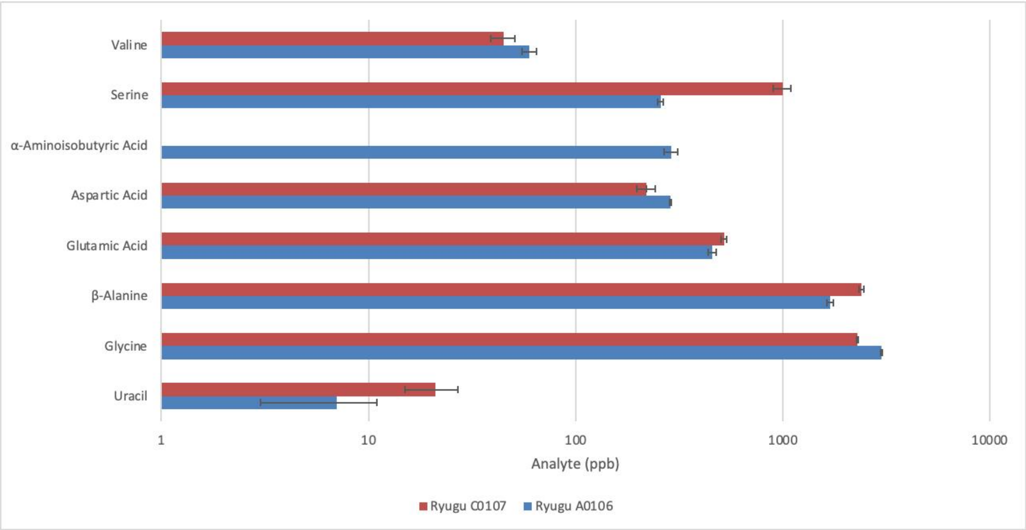

Figure 1. Organic compound concentrations in Ryugu samples A0106 and C0107 (log scale). Shown amino acids were chosen based on prevalence in the samples.

Note: Error bars represent ± standard deviation given for each analyte. Absence of a bar indicates that the analyte was "Below Quantitation Limit". Data were compiled in ng/g (equivalent to ppb). Analytes below detection or quantitation limits in both samples were omitted. Custom error bars were applied using standard deviations reported in cited sources.

Source: Uracil data were taken from Oba et al. [5], and amino acid data from Potiszil et al. [24]. The numerical values used for the creation of **Figure 1** can be found in the Data Availability Statement.

Distinctly, both serine and α-aminoisobutyric acid demonstrated differing concentrations between samples, with serine being higher in C0107 and α-aminoisobutyric acid only being above the quantitation limit in A0106. As a higher concentration of serine occurs in the sample beneath Ryugu's surface, this suggests the likelihood of depth-dependent preservation. However, the indigenous status of serine in asteroid material is uncertain. Chan et al. [29] note that serine displays a low enantiomeric ratio in thermally affected carbonaceous asteroids, raising the possibility that at least a portion of the detected serine could reflect terrestrial sample contamination rather than genuine depth-dependent preservation. Conversely, α-aminoisobutyric acid was only detected in sample A0106, coming from Ryugu's surface. This distribution is notable, as other amino acids displayed relatively similar or elevated levels in C0107, but the difference in detection seen here is over 100 parts per billion. This difference could result from differing depths, and consequential environments of the two sample sites, but more research is needed to determine the exact cause of this measurement, particularly given α-aminoisobutyric acid's terrestrial rarity as a non-proteinogenic amino acid [28].

The major elemental composition of carbon, hydrogen, nitrogen, oxygen, and sulfur comprised 21.3 ± 1.4 wt% of the sample A0106, with these elements being the most prevalent found in Earth's crust [11]. Particularly significant was the detection of nucleobases, the nitrogenous bases that constitute the building blocks of nucleic acids. Using acid hydrolysis to break down larger macromolecules and high-performance liquid chromatography coupled with electrospray-ionization high-resolution mass spectrometry (HPLC/ESI-HRMS), the nucleobase uracil was identified in both A0106 and C0107 samples [5]. In sample A0106, Oba et al. found the amount of uracil to be approximately 7 ± 4 ppb, while sample C0107 measured approximately 21 ± 6 ppb (see **Figure 1** for comparative analyte values) [5]. The nearly threefold difference in uracil concentration between these two sites is scientifically significant beyond simply demonstrating heterogeneity. Sample A0106 was collected from Ryugu's equatorial ridge, a surface region subject to prolonged exposure to solar radiation and micrometeorite bombardment, while sample C0107 was collected from material excavated from beneath the surface by the Small Carry-on Impactor deployed by the Hayabusa2 [5,17]. The substantially higher uracil concentration in the subsurface sample suggests that surface weathering may have degraded nucleobases over time, with interior material preserving a more complete organic inventory than surface-exposed regolith.

While the concentrations of these bases are modest, such detections are extraordinary because nucleobases are rarely confirmed in extraterrestrial materials at such concentrations. To contextualize these values, one part per billion represents one microgram of a substance per kilogram of sample material, a concentration so minute that its detection required the most sensitive analytical techniques currently available, including HPLC/ESI-HRMS [5]. If these values were due to contamination, sporadic and low-level detections without any relationship to sample collection depth or surface exposure history would be expected. However, the pattern of concentration differences observed between A0106 and C0107 for the majority of analytes, which correlates with sample collection depth, is more consistent with an indigenous origin than with terrestrial contamination [5,12]. As the vacuum of space lacks many of the rapid weathering processes present on Earth, leading to a mostly unchanging environment, the detection of uracil in both samples implies a long-term prior presence of nucleobases within Ryugu [14].

More recent research has allowed for further analysis of Ryugu samples, resulting in the detection of all five nucleotide bases in Ryugu samples A0480 and C0370, which were gathered from the surface and sub-surface locations, respectively [2,16,30]. Using both HCl and H_2O extracts, Koga et al. [30] utilized a similar HPLC/ESI-HRMS technique. They identified all five nucleotide bases in the HCl extracts of both samples, and similarly detected all five bases in the H_2O extracts of A0480, but only four in the H_2O extract of C0370, with the nucleobase adenine being below detection limit [30]. The significance of this finding is twofold: it confirms that Ryugu's nucleobase inventory extends beyond uracil alone, and the extraction-dependent variation in adenine detection raises questions about compound stability under different extraction conditions and the degree to which extraction methodology may influence apparent organic inventories. The discrepancy between HCl and H_2O extracts warrants further investigation, as it suggests that the choice of solvent may selectively recover or degrade specific nucleobases, with implications for how comprehensively any single extraction protocol can characterize the full organic inventory of a primitive asteroid sample.

3.2. Organic Compounds and Nucleobase Detection in Bennu Samples

Early analyses of samples returned from Asteroid (101955) Bennu by the OSIRIS-REx mission have yielded an organic inventory that both corroborates and extends the findings from Ryugu [10,31]. These samples were taken from a crater site within another crater, which was chosen due to its low albedo and varying regolith coloration[11]. A study by Mojarro et al.[31] identified prebiotic soluble organic compounds in Bennu samples consistent with heterogeneous weathering on the asteroid's parent body, paralleling the alteration history inferred for Ryugu. The bulk elemental composition of Bennu samples similarly reflects an abundance of carbon, hydrogen, nitrogen, oxygen, and sulfur, with Glavin et al.[13] reporting abundant ammonia and nitrogen-rich soluble organic matter consistent with a volatile-rich primitive carbonaceous environment. Among the most significant detections are amino acids, identified across multiple Bennu sample analyses and representing a chemically diverse array comparable to those confirmed in Ryugu[31].

As with Ryugu, the presence of both proteinogenic and non-proteinogenic amino acids in Bennu samples is more consistent with an abiotic origin than with terrestrial biological contamination. Biological processes on Earth strongly favor a narrow subset of amino acids, a pattern inconsistent with the broad chemical diversity observed across both sample sets[24,26,32]. The detection of nucleobases in Bennu samples further mirrors the findings from Ryugu, with the additional confirmation of ribose and other biologically relevant sugars by Furukawa et al.[33] representing the most notable extension of Bennu's organic inventory beyond what has currently been confirmed in Ryugu material (see comparison in **Table 1**). The detection of ribose is particularly significant because it is the five-carbon sugar component of RNA nucleotides, meaning Bennu samples contain at least two of the three structural components required for nucleotide assembly: the nucleobase and the sugar. Magnesium-sodium phosphates were also reported; however, these differ from the organophosphates that would constitute the third structural component of a nucleotide[10,31]. Prior to sample return, orbital observations by Simon et al.[19] had already identified widespread carbon-bearing materials across Bennu's surface, providing early evidence of its carbonaceous nature that has since been confirmed and substantially expanded by laboratory analysis of returned samples.

Table 1. Detection of nucleobases and amino acids in Ryugu and Bennu samples.

Compound	Class	Ryugu A0106	Ryugu C0107	Ryugu A0480	Ryugu C0370	Bennu
Uracil	Nucleobase	+	+	+	+	+
Thymine	Nucleobase	−	−	+	+	+
Cytosine	Nucleobase	−	−	+	+	+
Adenine	Nucleobase	−	−	+	+	+
Guanine	Nucleobase	−	−	+	+	+
Glycine	Amino acid	+	+	N/A	N/A	+
β-Alanine	Amino acid	+	+	N/A	N/A	+
Serine	Amino acid	+	+	N/A	N/A	+
Aspartic Acid	Amino acid	+	+	N/A	N/A	+
Glutamic Acid	Amino acid	+	+	N/A	N/A	+
Valine	Amino acid	+	+	N/A	N/A	+
Phenylalanine	Amino acid	−	+	N/A	N/A	+
Tyrosine	Amino acid	−	+	N/A	N/A	+
Alanine	Amino acid	−	−	N/A	N/A	+
Leucine	Amino acid	−	−	N/A	N/A	+
Isoleucine	Amino acid	−	−	N/A	N/A	+
Proline	Amino acid	−	−	N/A	N/A	+

Note: + = detected; − = not detected; N/A = not tested for in cited analyses. Table values reflect the presence or absence of analytes rather than their measured concentrations.
Source: Ryugu A0106 and C0107 data were collected from Oba et al.[5]; Ryugu A0480 and C0370 HCl extraction data from Koga et al.[30]; Ryugu amino acid data from Potiszil et al.[24]; Bennu data from Mojarro et al.[31]. Amino acid analytes that were not detected in any of the cited studies were eliminated from the table.

3.3. Assessment of Organic Compound and Nucleobase Detection

The organic inventories documented in Ryugu and Bennu samples are products of specific analytical choices and material constraints that influence what could be detected, at what sensitivity, and in what quantities. A critical assessment of what these inventories do and do not establish requires examining both the analytical techniques employed and the broader challenges of cross-mission comparison.

These methods, while advanced, have multiple limitations. The use of acid hydrolysis prior to HPLC/ESI-HRMS analysis, while necessary to break down macromolecular material and improve compound recovery, does have the potential to degrade or structurally alter labile organic compounds during processing, meaning that reported concentrations may underestimate the true abundance of some analytes in the original sample [34]. Additionally, HPLC/ESI-HRMS quantification is subject to ionization efficiency variability between compounds, meaning that the relative concentrations of structurally diverse analytes cannot be directly compared without compound-specific calibration standards—a challenge that is more likely to be encountered when analyzing complex extraterrestrial matrices for which many compounds lack available reference materials [35]. The modest sample masses returned by Hayabusa2 further constrain the range of analyses that can be performed, as the allocation of limited material across multiple analytical techniques introduces tradeoffs between the breadth and depth of characterization possible from any given sample aliquot [5,12]. Taken together, these limitations suggest that the organic inventories reported for Ryugu samples may represent a lower bound on the true complexity of the asteroid's chemistry, and that continued analysis of archived material using evolving analytical techniques is likely to reveal additional compounds or other discrepancies not detectable under current conditions.

These analytical constraints become particularly consequential when comparing the organic inventories of Ryugu and Bennu directly. The approximately twenty-two-fold difference in returned sample mass between OSIRIS-REx and Hayabusa2 has enabled a considerably broader range of analytical techniques to be applied to Bennu material, and it is not yet clear whether the more extensive organic inventory reflects a genuinely richer chemistry or simply greater analytical coverage of a comparable one [10,18]. This distinction is difficult to resolve without equivalent analyses applied to equivalent sample masses from both bodies, which the current material constraints do not permit. Additionally, these questions are particularly relevant when considering compounds confirmed in Bennu but not yet in Ryugu, most notably ribose. The absence of ribose in Ryugu samples should not be interpreted as evidence of its absence from the asteroid, as the sample mass constraints imposed on Ryugu analyses mean that compounds present at low concentrations may fall below current detection thresholds [12]. However, continued analysis of archived Ryugu material using improving analytical techniques may yet reveal sugars not detectable under prior conditions [5,12].

Interpretation of the current inventory differences between the two asteroids is further complicated by the heterogeneous nature of both sample sets. Mojarro et al. [31] explicitly note that the distribution of organic compounds across Bennu samples reflects heterogeneous geological processing on its parent body, meaning that the detected inventory may not be representative of Bennu's bulk composition and that different sample aliquots may yield substantially different organic profiles. The same caveat applies to Ryugu, where the concentration differences between A0106 and C0107 already demonstrate that local sampling conditions significantly influence apparent organic inventories. These uncertainties do not diminish the significance of the detections reported across both bodies, but they underscore the importance of treating current organic inventories as provisional snapshots of a more complex and variable chemistry rather than definitive characterizations of either asteroid.

4. Aqueous Alteration and Space Weathering

4.1. Aqueous Alteration

Asteroids do not encounter wind, precipitation, or biological weathering, but can still be altered by other processes [36]. The diversity of chemical compositions observed in Ryugu samples is hypothesized to have been shaped by aqueous alteration, a process in which liquid water reacts with silicate rocks and metal phases within the asteroid [9,37–39]. The energy driving these reactions is thought to derive primarily from the decay of aluminum-26 (26Al), a short-lived radioactive isotope that was abundant in the early solar system [40]. Grimm and McSween [40] demonstrated that 26Al decay within sufficiently large parent bodies could generate enough heat to melt internal water ice, producing the liquid water necessary to initiate aqueous alteration reactions throughout the rock matrix.

Studies of Ryugu indicate that aqueous alteration occurred primarily on the asteroid's parent body, rather than on Ryugu itself, though one study found that the levels of aqueous alteration varied between particles tested, with the sample taken from the surface demonstrating evidence of experiencing higher aqueous alteration than the sample gathered from beneath the surface [37,38]. During aqueous alteration, water and rock react under the influence of solar and isotopic heating, resulting in the formation of secondary minerals including phyllosilicates, carbonates, and nanometer-scale globules of organic matter, explaining the diversity of the material found within the Ryugu samples [37,38,41]. All of these secondary compounds are formed from the volatile elements common throughout the solar system, namely carbon, nitrogen, and oxygen.

At the mineral level, aqueous alteration occurs through a series of hydration and oxidation reactions in which anhydrous silicates and metal sulfides react with liquid water to produce hydrated secondary phases. The serpentinization reaction, for example, converts olivine and pyroxene into serpentine-group phyllosilicates, releasing hydrogen gas as a byproduct [42]. Carbonate minerals such as dolomite and breunnerite precipitate from dissolved carbon dioxide and magnesium ions in the aqueous fluid, while iron sulfides undergo oxidation to produce magnetite [29,35]. The nanometer-scale organic globules observed in Ryugu and primitive carbonaceous asteroid samples are thought to form through Fischer-Tropsch-type reactions or aqueous organic synthesis during this same alteration phase, producing complex macromolecular organic material from simpler precursors under the influence of mineral catalysts and elevated temperatures [24,37].

Evidence for aqueous alteration has similarly been identified in Bennu samples, with Mojarro et al. reporting that the distribution of organic compounds across Bennu's surface reflects heterogeneous alteration on its parent body [31,43]. The phyllosilicate mineralogy of Bennu samples is broadly comparable to that of Ryugu and CI chondrites, suggesting similar water-rock reaction histories, though differences in specific mineral phases indicate subtly different alteration conditions between the two parent bodies [31,44]. Additionally, recent analyses of Bennu samples showed that certain nitrogen- and oxygen-rich organic networks exhibit signatures of polymerization occurring during a pre-aqueous cryochemical phase on the parent body [45]. This heterogeneity in alteration history across two independently sampled carbonaceous asteroids highlights the diversity of aqueous processing that may have occurred across primitive parent bodies in the early solar system, and has direct implications for the uneven distribution of organic compounds observed within and between asteroid sample sets.

4.2. Space Weathering

An important factor in interpreting asteroid samples concerns space weathering: the chemical and physical alterations of asteroid surfaces caused by micrometeorite impact bombardment and ion implantation due to solar wind over geological timescales [36,46]. Because Ryugu's samples were sealed immediately upon collection, they preserve a largely unaltered composition. In contrast, meteorites recovered from Earth have often experienced terrestrial weathering, oxidation, and alteration, in addition to atmospheric entry effects [9,11]. This makes Ryugu samples more representative of the asteroid's original mineralogy and chemistry.

Space weathering effects have similarly been characterized in Bennu samples by Keller et al. [47], who identified comparable micrometeorite bombardment signatures and solar wind implantation effects on Bennu's surface. As with Ryugu, the return of sealed samples by OSIRIS-REx preserves a record of Bennu's surface chemistry that would be damaged by terrestrial weathering and atmospheric entry effects in meteorite samples, reinforcing the value of hermetic sample return for characterizing space weathering processes across different carbonaceous asteroid types [12,47].

The primitive chemical state preserved in Ryugu's sealed samples is further supported by the detection of presolar grains, microscopic particles whose isotopic compositions are interpreted as evidence of an origin prior to the formation of our solar system [15,48]. Unlike the bulk material of asteroids and meteorites, which formed primarily from the mixing and processing of solar nebula material, presolar grains retain the isotopic signatures of the individual stars in which they were synthesized [15]. Their presence in Ryugu samples confirms that the asteroid's parent body would not have experienced a level of heating or chemical processing sufficient to destroy them. Meteorites recovered on Earth have not only experienced terrestrial weathering, but also the shock and heating of atmospheric entry, both of which can damage or destroy presolar grains and further reduce their detectable abundance [49]. This makes Ryugu's returned samples uniquely valuable for presolar grain studies, as they preserve an additional line of evidence for the asteroid's status as one of the most chemically primitive bodies yet sampled [49].

Presolar grains have similarly been confirmed in Bennu samples by Nguyen et al. [50], who identified abundant supernova dust across two lithologies with heterogeneous distributions reflecting variable aqueous alteration across Bennu's parent body. The independent detection of presolar grains in both Ryugu and Bennu samples suggests that the preservation of pre-solar system material may be a broader characteristic of primitive carbonaceous asteroids, rather than an anomaly unique to Ryugu [49,50]. Together, the space weathering records preserved in Ryugu and Bennu samples—including surface alteration signatures, presolar grain abundances, and organic compound distributions—represent the most detailed comparative dataset currently available for understanding how primitive carbonaceous asteroids are modified over geological timescales, and how those modifications affect the preservation of their original chemical inventories [12,36,47,50].

4.3. Assessment of Alteration and Weathering Interpretations

While aqueous alteration is well-documented in both Ryugu and Bennu samples, its underlying physical and thermodynamic mechanisms remain a subject of active debate. Two main questions structure this debate: those relating to the chronology of the aqueous phase, and the origin of the heterogeneity observed within and between asteroid sample sets. A primary facet of this debate concerns the chronology of the aqueous phase, specifically whether it occurred as a single continuous event or via multi-stage episodic processing. The primary continuous model holds that liquid water was present solely during an early, prolonged window lasting several million years, directly driven by short-lived radionuclide decay [51,52]. This model outlines stable thermal and chemical cooling profiles where organic networks could evolve predictably via mineral catalysis. In contrast, episodic alteration models suggest that subsequent impact events on the parent body induced localized, pulsed shock heating and transient ice melting long after early radiogenic isotopes were extinct [53].

Weighing these two models is highly consequential for interpreting the organic data compiled from Ryugu and Bennu samples. A continuous early timeline favors sustained prebiotic synthesis, whereas episodic, impact-driven fluid pulses would intermittently expose labile organic compounds, such as soluble amino acids and nucleobases, to sudden thermal degradation, structural reconfiguration, or secondary hydrolysis. The organic concentration differences observed between samples A0106 and C0107—with subsurface material generally preserving higher concentrations of nucleobases and certain amino acids—are consistent with post-formation processing of surface-exposed material, implying that alteration history was not necessarily limited to a single early window. However, this interpretation does have some shortcomings, particularly the limited number of sample sites and available sample mass, as well as the confounding influence of space weathering on surface samples, which makes it difficult to attribute surface-subsurface differences exclusively to internal alteration chronology rather than external surface processes.

The origin of the chemical heterogeneity observed within Ryugu and Bennu samples is similarly contested. The onion shell model predicts systematic concentric zonation of alteration intensity within the parent body, with alteration degree decreasing with distance from the thermal center, producing predictable depth-dependent gradients in secondary mineral assemblages and organic compound distributions [51]. In contrast, Travis and Schubert [54] propose that hydrothermal convection within carbonaceous chondrite parent bodies redistributed heat and aqueous fluids dynamically, homogenizing the concentric zones predicted by the onion model and producing more irregular, heterogeneous alteration patterns across the body.

The compound-specific variation observed between Ryugu sample sites offers a tentative basis for evaluating these models. The depth-dependent concentration differences in uracil and serine between A0106 and C0107, combined with the heterogeneous presolar grain distributions documented by Nguyen et al.[50], are arguably more consistent with convective redistribution than with a simple onion shell gradient, since the observed patterns do not follow a uniform depth-dependent trend across all compounds. However, with only two sample sites and limited total sample mass, distinguishing between systematic depth-dependent gradients, localized convective heterogeneity, and episodic alteration signatures preserved at different depths remains beyond the resolution of the current dataset. This limitation points toward a broader interpretive opportunity for future research. If future multi-depth sampling of Ryugu or analogous primitive carbonaceous asteroids reveals systematic gradients in alteration indicators across multiple sites, that would favor the onion shell model and a predominantly continuous alteration history. Irregular heterogeneity across sites, by contrast, would favor convective redistribution or episodic processing. In this sense, the depth-dependent organic record preserved in returned asteroid samples may function as a stratigraphic proxy for parent body alteration history, provided that sufficient sample diversity becomes available to distinguish internal alteration from surface weathering effects.

These internal alteration uncertainties are further compounded by the effects of space weathering on the asteroid surface, which introduces an additional and partially overlapping source of uncertainty in interpreting the returned organic inventories. The timescales over which space weathering processes degrade surface organic compounds are not well constrained, making it difficult to quantify how much of the original organic inventory has been lost from surface-exposed material prior to sample collection[36,47]. The depth to which space weathering effects penetrate below the asteroid surface also remains poorly understood, complicating interpretation of the concentration differences observed between surface and subsurface samples in both Ryugu and Bennu. Furthermore, the degree to which space weathering effects observed on returned samples accurately reflect conditions on the asteroid surface prior to the disturbance caused by sample collection itself introduces an additional source of uncertainty that is difficult to fully account for[12,46,47]. These limitations underscore that the organic inventories currently documented in Ryugu and Bennu samples, while unprecedented in their preservation relative to meteorite collections, represent a partial and potentially weathering-biased record of the original chemistry of these primitive carbonaceous bodies.

5. Ivuna-Type Carbonaceous Chondrites and Asteroids: Composition and Origins

5.1. CI Chondrite Characteristics and Classification

Ivuna-type carbonaceous chondrites, formally known as CI Chondrites, are a class of meteorites characterized by bulk elemental abundances that closely match the solar photosphere for condensable elements, excluding hydrogen and helium, which escape as gases[1,11,22]. Because of their similarity in composition to the Sun, they are thought to represent some of the most chemically primitive materials in our solar system, preserving a record of early solar system composition[7]. This is due to a lack of observed rock evolution and erosion, as well as the presence of presolar grains[14,15,55]. Like Asteroid (162173) Ryugu, CI Chondrites contain water and organic molecules with an elemental composition consistent with that of the solar photosphere[56,57]. Named after the Ivuna meteorite, which fell to Earth in Tanzania and was the first extraterrestrial object to be classified as a CI Chondrite, this class represents some of the most primitive materials available for study[22]. Despite having experienced extensive aqueous alteration, CI chondrites retain a bulk elemental abundance distribution that closely approximates solar composition for condensable elements[11].

CI chondrites are classified as undifferentiated meteorites, meaning their mineral and chemical makeup is broadly consistent throughout the samples, unlike differentiated bodies that have undergone melting and chemical segregation [9,22]. Like other chondrites, CI chondrites contain chondrules, millimeter- to centimeter-sized silicate spherules formed by rapid cooling in the solar nebula, although CI chondrites contain relatively few chondrules compared to other chondrite groups. The defining features of CI chondrites are their preservation of a wide array of volatile elements, including water, carbon, and nitrogen, their high degree of aqueous alteration, and their elemental abundances matching the solar system composition [58]. Because CI chondrites are meteorites, and therefore fragments of asteroid parent bodies recovered on Earth, their compositional characteristics provide a reference framework for interpreting the mineralogy and chemistry of their source asteroids, including Ryugu [25].

Due to Ryugu's composition of abundant volatile elements and organic compounds, its mineralogy and chemistry are best interpreted within the framework of Ivuna-type Carbonaceous Chondrites [37,59]. Specifically, the phyllosilicate-dominated mineralogy of Ryugu samples, their high degree of aqueous alteration, and their bulk elemental abundances approximating solar photospheric composition for condensable elements all mirror the defining characteristics of Ivuna-type Carbonaceous Chondrites outlined above [11,37]. The presence of amino acids, nucleobases, and presolar grains in Ryugu samples further parallels the organic and isotopic inventories documented in this chondrite class, and it is this combination of mineralogical, elemental, and organic similarities that motivates the CI chondrite classification and informs the detailed compositional comparison undertaken in Section 5.2 [11,59].

5.2. Ryugu Composition and Comparison to CI Chondrites

A landmark study by Yokoyama et al. [10] compared the mineralogy and elemental composition of Ryugu samples to CI chondrites and found remarkable similarities. The study concluded that Ryugu samples were compositionally comparable to CI Chondrites, but exhibited greater chemical purity than other CI Chondrite samples [14,36]. This class of meteorites is characterized by its undifferentiated and pure composition, but Ryugu was found to be more pristine and unaltered than the meteorite samples [4,11]. Samples taken from meteorites in the past may have been altered or contaminated while entering Earth's atmosphere, which would explain the differences [11].

Multiple studies examined the spectra and isotopic compositions of Ryugu samples in comparison to CI and other carbonaceous chondrite groups. Amano et al. [59] evaluated Ryugu's reflectance spectra in comparison to other CI Chondrites to assess parent body relationships. Additionally, the same study, along with several other studies, analyzed the samples from Ryugu and CI Chondrites by examining their reflectance spectra and concluded that the samples, despite some spectral differences, most likely originate from parent bodies with similar thermal and aqueous alteration histories [38,59,60]. These studies collectively concluded that there is a connection between the source materials of the CI Chondrites and those of Ryugu in both their age and formation history [11,56]. These studies also suggested that Ivuna-Class Carbonaceous Chondrites and Asteroid (162173) Ryugu have a common parent body with a chemically pristine composition, linking them both to the development of our solar system [56,57].

Additionally, the conclusion that Ryugu and CI chondrites share a common parent body, while supported by isotopic and compositional evidence, remains primarily inferential, as the direct confirmation of parent body relationships requires a level of sample comparison that the current analytical dataset does not yet fully permit [11,56,59]. These qualifications do not undermine the CI classification but highlight that it represents a well-evidenced interpretive framework rather than a definitive statement, and that continued analysis of both Ryugu samples and CI chondrite meteorites will be important for refining our understanding of their relationship.

5.3. Bennu Composition and Comparison to CI Chondrites

While Ryugu's composition aligns most closely with CI chondrites, Bennu's spectral and mineralogical characteristics place it in closer affinity with CM carbonaceous chondrites, a related but distinct class characterized by a somewhat lower degree of aqueous alteration and a slightly different secondary mineral assemblage [31,44,50,61]. CM chondrites share many of the defining features of CI chondrites, including phyllosilicate-dominated mineralogy and the preservation of volatile organic compounds, but differ in their water-to-rock ratios during aqueous alteration and in the specific carbonate and sulfide phases present. This distinction suggests that while Ryugu and Bennu likely originated in broadly similar regions of the early solar system and experienced comparable aqueous alteration processes, their parent bodies underwent subtly different alteration histories [62]. The comparison between the two asteroids therefore provides a natural experiment in how variations in parent body aqueous alteration affect the preservation and diversity of organic compounds, with Bennu's broader sugar inventory potentially reflecting differences in alteration temperature, duration, or water availability of Bennu's parent body relative to that of Ryugu's.

Bennu's amino acid inventory, while broadly comparable to Ryugu's in terms of compound diversity, has not yet been characterized at the level of detail necessary to make an equivalent assessment of potential synthesis mechanisms, demonstrating an important gap in the current comparative dataset that future analyses may be able to address [31,32]. These chemical distinctions, rooted in parent body processing, are further contextualized by evidence suggesting that Ryugu and Bennu share a broader collisional and dynamical history within the primitive asteroid belt.

The connection between Ryugu and CI chondrites extends beyond compositional similarity to questions of shared origin. Michel et al. [44] proposed that Ryugu's characteristic top shape, which is congruent with Bennu's, is consistent with collisional formation from a larger parent body, a process that would have redistributed and mixed material from different depths and alteration environments within that body. Delbo et al. [61] further examined the origins of both Ryugu and Bennu within the context of primitive inner-belt asteroid families using Gaia observatory data, finding that both asteroids likely originated from the same region of the asteroid belt, a finding that helps explain their broadly similar carbonaceous compositions despite differences in spectral classification and specific organic inventories [21]. Together, these studies suggest that the chemical similarities between Ryugu, Bennu, and CI chondrites reflect not only comparable formation environments but potentially a shared collisional and dynamical history within the primitive asteroid belt [44,61].

The distinction between CI and CM parent body chemistry is further reflected in the amino acid profiles of Ryugu and Bennu samples. In CM chondrites, the relatively high abundance of α-aminoisobutyric acid relative to glycine is a strong indicator of Strecker-cyanohydrin synthesis, which is an abiotic reaction pathway producing amino acids from aldehydes, hydrogen cyanide, and ammonia under aqueous conditions, as the dominant amino acid formation mechanism on their parent bodies [27,28]. In contrast, CI chondrites show characteristically low AIB abundance and glycine:β-alanine ratios at or near unity, indicating that Strecker synthesis was not the dominant pathway on CI-type parent bodies [27]. As discussed in Section 3.1, the amino acid profile of Ryugu samples, including low AIB abundance and a glycine:β-alanine ratio approaching unity in subsurface sample C0107, is consistent with CI-type parent body chemistry rather than CM-type Strecker synthesis [24,27,28].

5.4. Assessment of Chondrite Compositions and Classifications

The CI chondrite classification of Ryugu is well-supported by the combination of mineralogical, elemental, and organic evidence outlined in previous sections, yet the accumulated evidence from multiple independent lines of analysis raises a more fundamental question: whether the discrepancies between Ryugu and CI chondrite meteorites reflect genuine compositional differences between them, or instead reflect the degree to which the meteorite samples themselves have been altered from their original compositions.

The spectral evidence reviewed in Section 5.2 offers the first indication that the relationship between Ryugu and CI chondrites is more complex than a compositional comparison. Amano et al. [59] note that Ryugu samples exhibit reflectance spectra that cannot be fully reconciled with CI chondrite meteorites even after accounting for known weathering and entry effects, suggesting that the CI classification captures the dominant characteristics of Ryugu's composition without fully describing its spectral properties. This distinction carries practical implications for asteroid science beyond the classification of Ryugu itself, as reflectance spectra are among the primary tools used to identify primitive carbonaceous asteroids remotely—meaning that if Ryugu defines a spectrally distinct variant of CI-like composition, ground-based surveys may be systematically misidentifying or underrepresenting this asteroid class in the broader near-Earth population [59,60].

The amino acid evidence discussed in Section 5.3 provides an independent line of support for the same conclusion. The low AIB abundance and near-unity glycine:β-alanine ratio in Ryugu samples are consistent with CI-type parent body chemistry, but the specific values observed differ slightly from those documented in CI chondrite meteorites, a pattern that can be attributed in part to post-fall modification of the meteorite amino acid inventory through terrestrial biological contamination and hydrolysis [28,29]. If the amino acid profiles of CI chondrites have been modified by terrestrial processing to a degree that exceeds what contamination protocols can fully correct, then Ryugu's amino acid inventory may represent a less altered expression of the same underlying chemistry rather than a divergent one. The presence of abundant microchondrules in Ryugu with characteristics inconsistent with those in other CI chondrites adds further insight into this question. Genge et al. [63] investigated Ryugu samples in comparison to the CI chondrite Orgueil and suggested, based on their findings, that the two bodies may have formed under subtly different nebular turbulence conditions, meaning that some of the differences between Ryugu and CI meteorites may reflect genuinely distinct formation environments rather than post-fall alteration of the meteorites.

Taken together, these lines of evidence suggest that the question of whether Ryugu fits the CI chondrite classification may be less relevant than the question of whether Ryugu should serve as a revised reference standard for what pristine CI-like material actually looks like before terrestrial processing. The CI chondrite class is currently defined by reference to meteorites that, by definition, have survived atmospheric entry and varying periods of terrestrial exposure, which Ninomiya et al. [64] explicitly identify as potential sources of the compositional discrepancies seen between Ryugu and CI meteorites. Whether a hermetically sealed, uncontaminated asteroid sample like Ryugu might therefore provide a more accurate anchor point for the CI classification than the meteorites from which that classification was originally derived remains a question for future research, and one with significant implications for how the CI chondrite class is defined and applied in future asteroid science.

6. Discussion

6.1. Organic Synthesis Pathways and Abiotic Origin

The detection of amino acids, nucleobases, and sugars across two independently returned carbonaceous asteroid sample sets provides the strongest direct evidence to date that complex organic compounds form abiotically in extraterrestrial environments. Taken collectively, the organic inventories of Ryugu and Bennu are most consistent with synthesis through a combination of interstellar ice photochemistry and solar nebula processing, with subsequent modification during aqueous alteration on their respective parent bodies [24,37,38]. The co-occurrence of proteinogenic and non-proteinogenic amino acids in both sample sets, in proportions inconsistent with biological origin, argues against terrestrial contamination as a primary explanation and implies the possibility of abiotic synthesis pathways operating across a range of chemical conditions [24,26,32].

However, disentangling the relative contributions of interstellar synthesis, solar nebula chemistry, and parent body aqueous processing to the final organic inventory of either asteroid remains an unresolved challenge. Isotopic evidence from Potiszil et al. [24] points toward at least a partial interstellar origin for some amino acids in Ryugu, while the aqueous alteration histories of both parent bodies complicate direct inference of formation pathways from the returned samples alone [37–39]. The amino acid synthesis pathway comparison between Ryugu and Bennu, informed by the glycine:β-alanine ratios and AIB abundances discussed in Section 3.1 and the Strecker synthesis framework introduced in Section 5.3, suggests that while both asteroids preserve evidence of abiotic organic synthesis, the specific pathways active on their parent bodies differed in ways that are consistent with their broader mineralogical classifications [27,28]. These findings establish that abiotic organic synthesis may not be anomalous but rather a widespread feature of primitive carbonaceous parent bodies across the early solar system.

6.2. Comparative Organic Inventories

The broader organic inventory confirmed in Bennu samples relative to Ryugu raises the question of whether this difference reflects a genuinely richer chemistry or is primarily a consequence of the approximately twenty-two-fold difference in returned sample mass and the correspondingly broader range of analyses applied to Bennu material. This distinction matters because the interpretation of inventory differences is quite relevant to understanding how parent body processing shapes organic chemistry across different carbonaceous asteroid types. If the differences are largely analytical, they suggest that Ryugu's chemistry may be more comparable to Bennu's than the current data indicate, and that continued analysis of archived Ryugu material will progressively close the apparent gap. This can already be seen in the publication of Koga et al. [30], which demonstrated the presence of four nucleobases in Ryugu samples that were undetected in previous analyses.

However, if the differences are chemically meaningful, they point toward the alteration history and spectral classification differences between the two parent bodies, specifically the higher degree of aqueous alteration inferred for Ryugu's CI-like parent body relative to Bennu's CM-like parent body, as the primary driver of divergent organic inventories [31,44,61,62]. The evidence currently available is insufficient to fully resolve this question. The sample mass asymmetry between the two missions introduces an irreducible analytical bias that cannot be corrected without equivalent analyses on equivalent sample masses, which the current material constraints do not permit [10,18]. What can be determined is that the detection of the same compound types within two asteroids of different classes across two independently processed sample sets with different alteration histories and analytical protocols provides a stronger basis for concluding that these compounds are genuine features of primitive carbonaceous asteroid chemistry than either dataset could provide alone [12].

6.3. Key Unknowns and Current Controversies

Despite the significant advances represented by the Hayabusa2 and OSIRIS-REx sample returns, several fundamental questions remain unresolved. The lack of ribose in Ryugu, but the presence of the sugar in Bennu, could merely be a discrepancy due to the difference in sample size. However, if ribose is genuinely absent, as opposed to below detection limits, it raises questions about the sequence or conditions of abiotic organic synthesis. Ryugu contains many of the same amino acids and nucleobases that Bennu does, but the lack of ribose could suggest that different synthesis reactions and processes occurred on Bennu, resulting in the presence of ribose. This would expand the framework of abiotic development, indicating that these bio-relevant compounds can form from multiple reactions and environments [65].

Organophosphates are a critical compound of RNA and DNA and one noticeably absent from both the Ryugu and Bennu samples. Like ribose, organophosphates may be present, just in small quantities below the detection limits of HPLC/MS. This could be exacerbated due to the small sample mass of Ryugu material. A potential solution to this dilemma can be found in the method of ion chromatography coupled with high-resolution Orbitrap mass spectrometry (IC/Orbitrap-MS), which offers greater sensitivity and selectivity for phosphorylated organic compounds than the HPLC/ESI-HRMS approaches used in prior analyses, with detection limits as low as ~10 fmol in complex matrices [66].

The heterogeneity of these asteroids also informs the weighting of these samples, as one sample may not reflect the full composition of the asteroid. This is indicated by the uneven distribution of presolar grains across the asteroids' surfaces. The exact cause of this distribution is uncertain, but Nguyen et al. [50] attribute this heterogeneous distribution to variable aqueous alteration across Bennu's parent body, suggesting that regions of more intense alteration may have depleted presolar grain abundances through thermal processing. If this interpretation extends to Ryugu, where presolar grains have similarly been detected at variable abundances, it raises similar questions about whether the organic compound distributions observed across both asteroids reflect genuine chemical heterogeneity in their parent bodies or are instead an artifact of uneven alteration, which is a distinction that cannot be resolved without a more systematic sampling of both asteroid surfaces than current missions have permitted.

6.4. Broader Significance

These findings from Ryugu and Bennu should be understood in their proper scientific context. The detection of nucleobases, amino acids, and sugars in returned asteroid samples does not establish that asteroid impacts seeded early Earth with the molecular precursors of life, nor does it demonstrate that life exists or existed elsewhere in the solar system, though it does open doors to further research on those questions. What it does establish is that the molecular components most closely associated with life on Earth, compounds whose abiotic formation was once considered uncertain, are present in extraterrestrial environments in quantities and combinations that make them relevant to discussions of prebiotic chemistry, regardless of which specific origin hypothesis one finds most compelling [67–69].

The significance of the parallel Hayabusa2 and OSIRIS-REx missions extends beyond the individual findings from each asteroid. The detection of comparable organic compound classes across two independently sampled, independently processed carbonaceous asteroids with subtly different alteration histories provides a comparative framework that meteorite collections alone could not offer, and establishes a foundation for interpreting the growing catalog of returned extraterrestrial materials in a broader context [12,31,44]. The degree to which these findings are representative of primitive carbonaceous asteroids as a class, rather than anomalous features of Ryugu and Bennu specifically, remains an open question, and one that future sample return missions targeting additional carbonaceous bodies will be uniquely positioned to address.

The compositional evidence explored in Section 5.4 raises a related but broader question about the reference frameworks through which primitive asteroid chemistry is interpreted. If the discrepancies between Ryugu and CI chondrite meteorites reflect terrestrial contamination and atmospheric entry effects on the meteorite samples rather than compositional divergence, then returned asteroid samples may not merely supplement meteorite-based classification frameworks; they could provide a more exact model than our current framework can. Ryugu, in particular, as the most chemically pristine primitive carbonaceous body yet directly sampled, may represent a more accurate reference standard for CI-like composition than the meteorites from which the CI classification was originally derived [64]. Similarly, asteroid Bennu provides a comparative framework to the class of CM meteorites. Given its high variety in organic content, using Bennu as a reference may provide greater insight into currently unclassified primitive asteroids and their expected composition than the current set of meteorite samples. This does not invalidate existing classification schemes, but it suggests that as the catalog of returned asteroid samples grows, the field may need to develop classification frameworks that treat pristine samples of asteroid or even intercepted meteoroid material as the primary reference rather than as a complement to meteorite collections.

The definition of life as a self-sustaining chemical system capable of Darwinian evolution sets a high bar that the organic inventories of Ryugu and Bennu do not meet—nor should they be expected to [70]. What these findings do establish is that the molecular components most associated with life on Earth may not be unique to our planet. These samples open a new frontier for astrobiological research and with time may enlighten our understanding of both planetary and universal origins and development.

7. Conclusions

The Hayabusa2 and OSIRIS-REx missions have returned sealed, minimally contaminated samples from two primitive carbonaceous near-Earth asteroids, enabling unprecedented laboratory analysis of extraterrestrial organic material. Yokoyama et al.[10] found that Ryugu's composition is similar to that of Ivuna-Type Carbonaceous (CI) Chondrites, a rare class of meteorites whose bulk elemental abundances closely approximate our solar photospheric composition for many condensable elements. Several additional comparisons report that Ryugu is CI-like and in some respects appears more chemically pristine than CI meteorite samples analyzed on Earth[11,59]. This greater chemical purity is consistent with the preservation of indigenous organic material unmodified by atmospheric entry or terrestrial weathering, underscoring the value of hermetically sealed sample return for recovering the most primitive carbonaceous asteroid chemistry. Ryugu was found to contain all five canonical nucleobases alongside a diverse amino acid inventory and approximately 20,000 soluble organic compounds, with the combination of mineralogical, elemental, and organic similarities to CI chondrites implying an origin in a chemically primitive carbonaceous parent body[5,11,23,24]. These findings establish Ryugu as one of the most chemically primitive bodies yet sampled, offering a valuable window into the organic chemistry of the early solar system.

These findings are significantly reinforced by the analysis of samples returned from Asteroid (101955) Bennu by NASA's OSIRIS-REx mission in 2023. Bennu samples have confirmed the presence of nucleobases, amino acids, and bio-essential sugars including ribose, extending the organic inventory confirmed in Ryugu and establishing that such compounds are present across at least two independently sampled primitive carbonaceous asteroids[13,21]. The detection of magnesium-sodium phosphates in Bennu samples is notable, though these occur in mineral rather than organic form and do not constitute the organophosphate component required for complete nucleotide assembly[10,65]. Nguyen et al.[50] additionally confirmed the presence of presolar grains in Bennu samples, paralleling their detection in Ryugu and suggesting that the preservation of presolar system material may be a broader characteristic of primitive carbonaceous asteroids. The comparison between Ryugu and Bennu, two independently sampled carbonaceous near-Earth asteroids with subtly different alteration histories and organic inventories, provides a natural experimental framework for understanding how parent body processing shapes the organic chemistry of primitive asteroid bodies, and establishes a foundation for interpreting future asteroid sample returns in the same context[31,44].

Future studies of Ryugu and Bennu will benefit from continued curation and analysis of archived sample material, with ongoing characterization likely to reveal additional organic compounds as analytical techniques improve. Of particular significance will be the search for phosphate-bearing organic compounds in Ryugu samples, which would complete the set of nucleotide precursor components already partially confirmed across both bodies[5,10]. Specifically, the application of emerging techniques such as ion chromatography coupled with high-resolution Orbitrap mass spectrometry may be particularly significant for resolving the question of organophosphate presence in both sample sets[66]. Beyond Ryugu and Bennu, NASA's OSIRIS-APEX mission is currently en route to asteroid Apophis, a carbonaceous near-Earth asteroid whose close Earth flyby in 2029 will provide an unprecedented opportunity to study the effects of tidal forces on asteroid surface chemistry, while JAXA's Hayabusa2 is expected to engage in a fly-by mission of the NEA Torifune in 2026[10,71]. The expanding catalog of returned carbonaceous asteroid samples will allow increasingly robust comparisons of organic inventories across different asteroid types, alteration histories, and heliocentric formation zones, progressively refining our understanding of the distribution and diversity of prebiotic compounds in the early solar system[69].

The molecular components most associated with life on Earth—nucleobases, amino acids, and sugars—have now been confirmed across two independently sampled primitive carbonaceous asteroids, suggesting they may be widespread features of the early solar system rather than products unique to Earth. While significant questions remain about their formation pathways, prebiotic relevance, and relationship to the emergence of life, the Hayabusa2 and OSIRIS-REx missions have opened a new frontier in our understanding of the chemical history of the solar system that future sample return missions will continue to expand.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used Claude AI (Anthropic) in order to check grammar correctness of the manuscript and order/format citations in the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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