



Gelato: A Mission Concept for Comet Surface Sample Return

Mallory J. Kinczyk¹ , Gabriel E. Buffo² , L. Miché Aaron-Hennig³ , Spencer Boone⁴ , Eric Frizzell⁵ , Abigail Flom⁶ , Chinmayee Govinda Raj⁷ , Camilla Harris^{8,9} , Ali Hyder⁹ , Benjamin Idini¹⁰ , Vidu Jayanetti¹¹ , Spiridon Kasapis^{12,13} , Brennan McCann¹ , Emily Millman¹⁴ , Alvin Ngo¹⁵ , Mary Ringwood¹⁶ , Laura E. Rodriguez^{9,17} , Amanda Rudolph¹⁸

Karl Mitchell⁹, Alfred Nash⁹, and William Smythe¹⁰

¹ Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA

² Georgia Institute of Technology, Atlanta, GA, USA

³ Johns Hopkins University, Baltimore, MD, USA

⁴ Institut Supérieur de l'Aéronautique et de l'Espace, Toulouse, France

⁵ Politecnico di Milano, Milan, Italy

⁶ University of Hawaii at Manoa, HI, USA

⁷ Blue Marble Space Institute of Science, Seattle, WA, USA

⁸ Advanced Research Computing Centre, University College London, London, UK

⁹ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

¹⁰ University of California, Santa Cruz, CA, USA

¹¹ University of Southern California, Los Angeles, CA, USA

¹² Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA

¹³ Advanced Supercomputing Division, NASA Ames Research Center, Moffett Field, CA, USA

¹⁴ Washington University, St. Louis, MO, USA

¹⁵ Oklahoma State University, Stillwater, OK, USA

¹⁶ University of California, Santa Barbara, CA, USA

¹⁷ Lunar and Planetary Institute/USRA, Houston, TX, USA

¹⁸ Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC, USA

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Abstract

Understanding the role of comets in solar system formation and evolution has continued to be a driving question in planetary science. It is believed that comets host a record of presolar history and early planet formation and likely delivered volatiles and organic materials to the inner solar system. Previous missions performed in situ compositional analysis of cometary coma materials. However, coma materials are thought to be heavily processed and therefore not necessarily representative of the nucleus from which they are derived. Laboratory analysis of a comet nucleus sample would provide important ground truth for remote observations of comet materials. Gelato is a comet surface sample return mission concept studied by the NASA Jet Propulsion Laboratory's 2022 Planetary Science Summer School that would address critical questions outlined in the 2023–2032 Planetary Science and Astrobiology Decadal Survey and the New Frontiers 4 Announcement of Opportunity related to the nature of comet formation and the origin of solar system materials. Central to Gelato's objectives are deciphering the early compositional diversity of radionuclides in the protoplanetary disk, elucidating the role of comets in transporting volatiles to Earth, and understanding the origins of biologically relevant organic matter that may have influenced the origin of life on Earth. Building on the rich dataset from the Rosetta mission, Gelato would explore and sample the Jupiter-family comet 67P/Churyumov–Gerasimenko. The spacecraft would use a BiBlade sampling chain to collect a single sample that would be stored on board at a noncryogenic temperature with separate volatiles containment and returned to Earth for analysis.

Unified Astronomy Thesaurus concepts: Comets (280); Asteroids (72); Small Solar System bodies (1469); Short period comets (1452); Comet volatiles (2162); Comet origins (2203); Biosignatures (2018)

1. Introduction

Comets are often thought to host the most intact record of the early solar system. Traditionally, these objects were thought to have formed in the cold outer reaches of the solar system (F. L. Whipple 1950), potentially preserving some of the most primordial materials. Not until dedicated spacecraft missions were sent to observe and analyze comet materials at close range could a more complex picture of the comet lifecycle and its role in solar system evolution be constructed (M. J. Belton et al. 2007; K. Kretke & H. Levison 2015;

D. Bockelée-Morvan et al. 2016). Comet science has progressed substantially in the past several decades from primarily telescopic observations prior to the 1980s to flyby observations such as that of the International Cometary Explorer, which performed the first cometary flyby in 1985 (T. T. Von Rosenvinge et al. 1986). Since then, multiple spacecraft have performed direct in situ and returned sample analysis of coma materials. The National Aeronautics and Space Administration's (NASA) Deep Impact mission was the first to probe the nucleus of a comet via an impactor in 2005, shedding light on the structure and composition of the interior of comet 9P/Tempel 1 (M. F. A'Hearn et al. 2005). The Stardust mission returned coma samples of 81P/Wild 2 to Earth in 2006 (D. Brownlee 2014), and the European Space Agency's (ESA) Rosetta mission performed in situ analysis of coma and surface materials at 67P/Churyumov–



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Gerasimenko (67P) from 2014 through 2016 (K.-H. Glassmeier et al. 2007). The observations from these missions have not only shed light on comet composition but also highlighted the need for laboratory analysis of the cometary nucleus to fully understand the role comets play in solar system formation and evolution.

NASA's Stardust mission visited the Jupiter-family comet (JFC) 81P/Wild 2 and collected coma samples in an aerogel sampler, which was returned to Earth in 2006. Analysis of these samples identified familiar high-temperature meteoritic materials composed of chondrule- and calcium-aluminum-rich inclusion (CAI)-like particles, though these were not associated with a specific type of meteorite (D. Brownlee 2014). Given that these refractory components are accreted in the hot regions of the solar nebula, this was a surprising result, suggesting that comets are formed from a diverse population of materials. This has implications for models of material transport in the solar system (E. R. Scott & A. N. Krot 2005; D. Nakashima et al. 2012; D. Brownlee 2014). While Stardust successfully returned cometary material for laboratory analysis, several aspects of the sample limited possible analysis: (1) the sample size was small, (2) materials were potentially modified by the collection mechanism, (3) particles did not contain enough long-lived radionuclides that could be used for absolute age dating, and (4) it is unclear to what extent coma materials are representative of the bulk cometary nucleus. In addition, the nature and design of the collection did not allow for highly volatile species to be returned.

ESA's Rosetta mission, which launched in 2004 March, aimed to orbit, land on, and perform in situ analysis of comet 67P. The spacecraft entered orbit in 2014 August and tracked the comet through perihelion. Rosetta had a number of science goals focused on characterizing the nucleus surface morphology, composition, and dynamic processes to understand cometary origins and elucidating the relationship between comets and both the interstellar medium (ISM) and solar system evolution (K.-H. Glassmeier et al. 2007). It was found that 67P is a dynamic object with a rapidly changing landscape, including both diurnal and seasonal cycles (S. P. Birch et al. 2017; M. R. El-Maarry et al. 2019; O. Groussin et al. 2025). Although the landing phase of the mission was cut short, due to the harpoon malfunction on the Philae lander (S. Ulamec et al. 2016), Philae was able to provide additional information about the comet surface, such as its low compressive strength (R. Roll et al. 2016; P. Heinisch et al. 2019; L. O'rourke et al. 2020). However, many of the outstanding questions in cometary science require sample analysis at resolutions that only ground-based laboratories are currently capable of, necessitating a sample return mission.

This paper provides a summary of the Gelato mission concept, a pre-Phase A comet surface sample return (CSSR) mission concept study conducted over the course of 10 weeks by the 2022 NASA Jet Propulsion Laboratory's (JPL) Planetary Science Summer School (PSSS). The PSSS brings together a diverse pool of early-career scientists and engineers to gain experience in designing a scientific mission concept from first principles. In Section 2, we present an overarching view of the mission, delineating its foundational science goals and objectives, and their relevance to the 2023–2032 Planetary Science and Astrobiology Decadal Survey, Origins, Worlds, and Life (National Academies of Sciences, Engineering, and Medicine et al. 2023) (Decadal) and the New Frontiers 4 (NF4)

Announcement of Opportunity (AO)¹⁹ (2017). Section 2 presents a high-level overview of the scientific goals and objectives of the Gelato mission and their relevance to the Decadal. Section 3 addresses the scientific payload and sampling mechanism, including a discussion on the protocols and methodologies for sample curation and analysis. The mission architecture, including comet and sample site selection and the concept of operations, is described in Section 4. Finally, Section 5 presents details on the NF4 AO requirements, spacecraft subsystems, and development strategies.

2. Mission Overview

Here we present Gelato, a CSSR mission concept study conducted by the 2022 NASA JPL PSSS that would collect and return to Earth a noncryogenic nucleus sample from comet 67P. By doing so, the mission would address high-priority science questions outlined in the Decadal and the NF4 AO. The goal of the mission is to characterize the elemental, isotopic, and structural composition of organic and inorganic matter from the cometary nucleus in order to determine the following: (1) whether early compositional reservoirs of short-lived radionuclides (SLRs) in the protoplanetary disk were homogeneous or heterogeneous between the inner and outer solar system, (2) what role comets played in the delivery of volatiles to Earth's atmosphere and interior, and (3) whether comets could have sourced biologically relevant organic matter that facilitated prebiotic chemistry and contributed to the homochirality of life on Earth.

In order to accomplish these objectives, Gelato would revisit comet 67P, making use of the extensive mapping conducted by the Rosetta mission. Gelato's mission timeline (Figure 1) would include a reconnaissance phase consisting of a high-altitude mapping orbit (HAMO) for selection and context characterization of up to four candidate sample sites and a low-altitude mapping orbit (LAMO) for detailed compositional and morphological characterization of the candidate sites to select a final sampling location. The spacecraft would then rendezvous with comet 67P to perform noncryogenic sample collection using a BiBlade sampling chain. Upon completion of the sample collection, Gelato would depart from the comet and begin its return cruise toward Earth, whereupon final rendezvous with Earth the Sample Return Capsule (SRC) would be ejected from the spacecraft and deliver the sample to Earth for laboratory analysis at the designated sample curation facility.

The main trade spaces explored for this mission focused on maintaining the integrity of the collected sample, selection of the sampling site, and the mechanism used for the sampling. The mechanism selected for this study was the BiBlade sampling chain to extract a single surface sample of 133.25 g. Site selection would favor recently exposed subsurface material, characterized using a narrow angle camera (Lunar Reconnaissance Orbiter Camera heritage) and a hyperspectral imager (Compact Reconnaissance Imaging Spectrometer for Mars heritage) to search for changes since the Rosetta mission. Based on the high instrument heritage and minimal science payload, the total cost of the mission is \$928.4 million (Fiscal Year 2025 (FY25)), which is within the cost cap defined by the NF4 AO.

¹⁹ <https://newfrontiers.larc.nasa.gov/NF4/announcements.html>

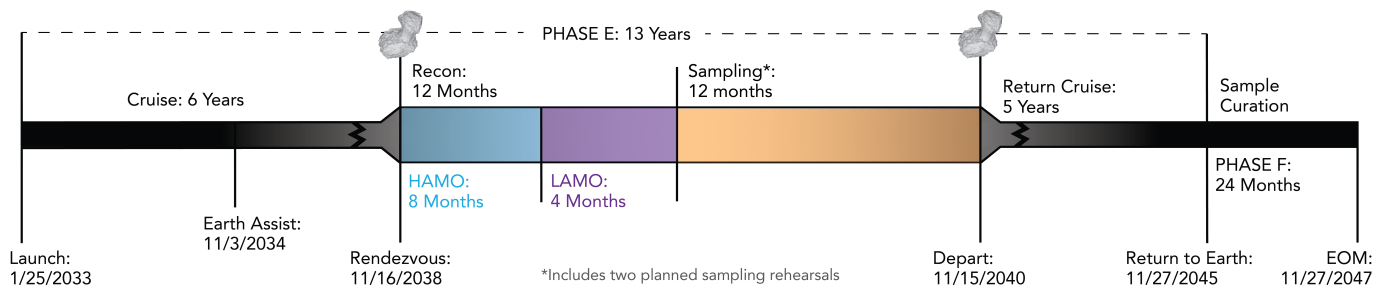


Figure 1. Gelato mission timeline: Phases E and F.

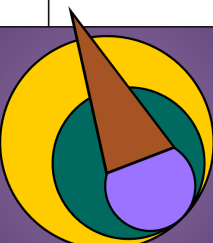
Goals	Science Objectives	Science Measurement Requirements	Instrument Requirements	Mission Requirements
Did nearby supernova trigger molecular cloud's collapse into pre-solar disk? - DS PQs Q1, Q2, Q3	O1: Determine whether early compositional reservoirs of short-lived radionuclides in the protoplanetary disk were (1) homogenous or (2) heterogenous between the inner solar system CAI and Chondrule forming regions and the outer solar system comet's formation region.	1.1 26Mg/24Mg, 26Mg/25Mg, 27Al/24Mg, 26Al/27Al ($2\sigma < 8$ ppm) for age and abundance	SIMS	Sample Handling Requirements: Total Sample Mass: ≥ 29 g Sampling depth: >100 nm Curation sample temp: $<25^{\circ}\text{C}$ (long-term storage @ -80°C) SRC Requirements: Hermetic seal; Temperature control at $<25^{\circ}\text{C}$; Separate volatiles containment
		1.2 52Cr/50Cr, 53Cr/52Cr, 54Cr/52Cr, 55Mn/52Cr, 53Mn/55Mn for age comparison to Al-Mg and to date alteration ($2\sigma < 14$ ppm, <1 My)		
		1.3 206Pb/204Pb, 207Pb/206Pb, 207Pb/235U, 206Pb/238U ($2\sigma < 1$ ppb) for absolute age ($2\sigma < 1$ My)	MC-ICP-MS	
What role did comets play in the delivery of volatiles to Earth's atmosphere and interior? - DS PQs Q3, Q10	O2: Determine whether volatiles were predominantly delivered to Earth via an early bombardment of 67P-like comets.	2.1 Abundance of stable isotopes of H (for $\delta\text{D} \pm 10\text{‰}$) in H_2O	GC-MS/IRMS	
		2.2 Abundance of stable isotopes of N (for $\delta\text{N} \pm 10\text{‰}$) in NH_3 and N_2		
		2.3 $^{136}\text{Xe}/^{132}\text{Xe}$ and $^{128}\text{Xe}/^{132}\text{Xe} < \pm 0.02$	Noble Gas Mass Spec	
2.4 $^{82}\text{Kr}/^{84}\text{Kr}$ and $^{86}\text{Kr}/^{84}\text{Kr} < \pm 0.02$				
		2.5 $^{36}\text{Ar}/^{38}\text{Ar}$ to $< \pm 0.03$		
Did comets deliver biologically-relevant organics to Earth, and if so, what were the origins of these cometary molecules? - DS PQs Q9, Q10	O3: Determine whether comet 67P is host to biologically relevant molecules and if so, whether they formed in presolar interstellar environments, the protoplanetary disk, or as a consequence of parent-body processes.	3.1. Amino acids (<10 ppm), hydroxy acids (<10 ppm), N-heterocycles (<10 ppb), sugar/derivatives (<10 ppb), fatty acids (<10 ppm)	LC-MS , GC-MS	
		3.2. Compound-specific isotope ratios in IOM and biologically-relevant SOM. IOM: $\delta\text{D}: \pm 100\text{‰}$, $\delta\text{N}: \pm 100\text{‰}$, $\delta\text{C}: \pm 50\text{‰}$, $\delta\text{O}: \pm 20\text{‰}$ SOM: $\delta\text{D}: \pm 10\text{‰}$, $\delta\text{N}: \pm 2\text{‰}$, $\delta\text{C}: \pm 1\text{‰}$	IOM: NanoSIMS SOM: LC-HRMS, GC-IRMS	
		3.3. Coordinated analysis of organic molecules (res. < 100 nm) with a Pearson correlation to statistically relate the association of organic molecules with presolar grains, ices, volatiles, metals, and minerals	XRF, SEM-EDS, Raman, Nano-SIMS, L2Ms	
		3.4. Enantiomeric excess: $[\% \text{D} - \% \text{L}]$ for amino acids, hydroxy acids, and sugars/derivatives (0-100% ee)	LC-HRMS	
		Reconnaissance Requirements		Mission Requirements
		R1. Near-global ($>90\%$) surface morphology via images (to <0.5 m scales) for sample site selection to avoid obstacles and target recently exposed material	Color Camera: GSD: <0.25 m SNR >20	HAMO @ 25 km LAMO @ 7 km Polar orbit
		R2. Near-global ($>90\%$) distribution of exposed minerals with $\pm 10\%$ abundance precision per (≤ 100 m) ^{2} to select sample site with: (O1) the mineral plagioclase for chronology, (O2) H_2O and CO_2 ice for volatiles work, and (O3) C-H bonds in organics	Hyperspectral Imager: Spectral Range: $0.8\text{--}4.5\ \mu\text{m}$ Spectral Res.: <5 nm GSD: <33 m SNR >180	Pointing Stability: <20 arcsec/sec Nadir Pointing

Figure 2. The STM summarizes the Gelato mission goals and science objectives, along with the corresponding measurement, instrument, mission, and reconnaissance requirements. "Sample Handling Requirements" refer to those required from launch through sample curation. For a full list of requirements, refer to the full STM in Appendix C.

2.1. Science Goals and Relevance to Decadal Survey and New Frontiers 4 Announcement of Opportunity

The NF4 AO requires that a CSSR mission (1) acquire and return to Earth for laboratory analysis a macroscopic comet nucleus surface sample, (2) characterize the surface region sampled, and (3) preserve sample complex organics. Gelato's science objectives (Sections 2.2–2.4) would collectively achieve these requirements. Characterization of the surface region is addressed in the "Reconnaissance Requirements" section of the Science Traceability Matrix (STM; Figure 2) and discussed in Section 3. The Decadal poses numerous questions regarding the origin and evolution of the group of primitive bodies in the solar system that includes asteroids and comets. The Gelato mission would directly address questions concerning the evolution of the protoplanetary disk (Question 1), accretion in the outer solar system (Question 2), origin of Earth and inner

solar system bodies (Question 3), insights from terrestrial life (Question 9), and dynamic habitability (Question 10). The Goals column of Figure 2 outlines the objective-specific relevance for each question.

Specifically, Objectives 1 and 2 address Question 1.1 on the initial conditions in the solar system, Question 1.2 on the formation and evolution of gas and solids in the protoplanetary disk, Question 2.2 on the control of composition of material that formed the giant planets, and Question 3.6 on the source of primordial inventories of volatile elements and compounds in the inner solar system. Objective 3 specifically addresses Question 9a on the influence of volatiles, impacts, and planetary evolution in early solar system environments on emergence and evolution of life on Earth and Question 10.4a on the identity, formation, and contribution to prebiotic chemistry of organic compounds in the early solar system.

2.2. Objective 1: Determine Whether Early Compositional Reservoirs of Short-lived Radionuclides in the Protoplanetary Disk Were Homogeneous or Heterogeneous between the Inner and Outer Solar System

SLRs are a key tool in characterizing the early solar system because they have short enough half-lives that they may have been sourced from nearby dying stars close to the beginning of our solar system's formation or they would likely have decayed before incorporation (H. McSween & G. Huss 2022). Determining initial isotopic abundances, such as $^{26}\text{Al}/^{27}\text{Al}$, is achieved by measurements of the earliest CAIs (the oldest known solar system objects; L. E. Nyquist et al. 2009; G. J. MacPherson et al. 2013), as well as chondrules (J. Villeneuve et al. 2009; K. Nagashima et al. 2017) and differentiated planetesimals (M. Bizzarro et al. 2005). However, the initial value of $^{26}\text{Al}/^{27}\text{Al}$ (short-lived compared to a stable Al isotope) decreases drastically over time, and only material from the first 3 million yr after CAI formation can yield measurements that distinguish between existing models of solar system formation (G. J. MacPherson et al. 1995). Furthermore, the reprocessing history of terrestrial samples makes it difficult or impossible to determine material origin location (e.g., inner vs. outer disk). The canonical model asserts that the initial distribution was overall homogeneous in the solar system, with small heterogeneities throughout the disk (K. Thrane et al. 2006; N. Dauphas et al. 2008). However, the initial distribution of ^{26}Al in the solar system remains controversial (T. Gregory et al. 2020). If a sample contains insufficient amounts of long-lived absolute geochronometers (e.g., Pb–Pb), the canonical value is used as a reference point for dating SLR systems. If SLR heterogeneity existed in the early solar system, then the canonical model should not be used in all cases, depending on location of origin within the disk.

The canonical model is based on samples from the inner solar system. Normal CAI measurements show a bimodal distribution with one peak at 5×10^{-5} initial $^{26}\text{Al}/^{27}\text{Al}$ (canonical abundance) and another peak at 0 initial $^{26}\text{Al}/^{27}\text{Al}$ (G. J. MacPherson et al. 1995). The peak at 0 is thought to be due to reprocessing of material and therefore not a valid measurement of the early abundance of ^{26}Al . The peak at the canonical value is thought to be representative of the ^{26}Al available during CAI formation in the early inner solar system, and that is the value used in studies that assume a homogeneous early solar system. However, a group of CAIs referred to as Fractionation and Unidentified Nuclear effects (FUN) CAIs show abundances at 0 but also the presence of other isotopic anomalies, which contradicts the hypothesis that CAI samples that show no initial ^{26}Al are all reprocessed.

Several hypotheses exist for the presence of FUN CAIs: (a) the inclusions formed or were remelted after the ^{26}Al decayed but managed to retain their other effects, (b) they formed before ^{26}Al was introduced into the solar system, and (c) they were formed at the same time as other CAIs but in a disk heterogeneity without ^{26}Al . Two major hypotheses have to do with the spatial distribution of ^{26}Al and its introduction into our solar system's material, which are intrinsically tied to models for the initial conditions and formation of our solar system. For example, it is hypothesized that the collapse of the molecular cloud into our protoplanetary disk may have been triggered by a supernova explosion that would have introduced ^{26}Al (A. Cameron & J. Truran 1977; H. A. Vanhala &

A. P. Boss 2002). The supernova trigger scenario could result in a heterogeneous distribution of SLRs between the inner and outer parts of the solar system. Evidence for supernova-triggered cloud collapse is seen in preserved meteorites, where isotopic anomalies suggest that modifications result from a supernova shock front. However, these anomalies could also exist as the result of turbulence dissipation and the influence of magnetic fields over long periods of time (A. Cameron & J. Truran 1977; H. A. Vanhala & A. P. Boss 2002). Alternatively, ^{26}Al could have been sourced by one or more dying stars at a different time without necessarily involving a supernova (H. Tang & N. Dauphas 2012). There is a need for measurements of minimally modified samples from the earliest days of the solar system that are constrained in time of formation and location in the disk in order to distinguish between models for the formation of our solar system and to test the validity of the canonical model for radiogenic dating. Comets are an excellent reservoir of outer solar system material that should be minimally reprocessed since the formation of the solar system, making comet samples ideal for addressing questions of the spatial and temporal distribution of ^{26}Al .

The Stardust mission analyzed samples from Comet Wild 2 and took some measurements of ^{26}Al in their samples. However, these samples have too little mass for dating other isotopic systems to confirm their age, such as Pb–Pb. This led to the assumption of the canonical value for the analysis of ^{26}Al in those samples (T. Gregory et al. 2020). The Gelato mission would collect a higher-mass sample in order to measure multiple systems, including the ^{26}Mg required to obtain ^{26}Al initial abundance. This would help constrain the outer solar system origin, age, possibility of alteration, and ^{26}Al initial abundance, all of which are needed to test the canonical model and hypotheses for solar system formation such as the supernova trigger hypothesis.

2.2.1. Sample Requirements

Detection of the decay products of interest, along with their stable isotopes, is performed through mass spectrometry. The SLRs (Al–Mg, Mn–Cr) can be measured through nondestructive methods (E. M. Van Kooten et al. 2016; K. Li et al. 2020; K. Fukuda et al. 2021), while the whole rock sample must be crushed and analyzed (L. Yang 2009; P. Koefoed et al. 2016; Z. Deng et al. 2021) in order to perform Pb age dating, due to the low abundance of Pb. The low abundances of Pb and U as compared to the other radionuclide systems of interest drive the required sample mass. As identified by A. Westphal et al. (2017), a minimum sample mass of 20 mg should be collected in order to perform Pb dating. Using this mass and assuming at least 10 trials are required for statistical significance, along with a conservative estimate of 1:1 ice-to-dust ratio on the comet surface, a 50% mass margin, and a 75% general margin, we arrive at a minimum required sample mass of 3.2 g. In order to compare the surface material from our selected comet with inner solar system CAI measurements, the measured $\Delta^{26}\text{Mg}$ (from which the initial abundance of ^{26}Al is inferred) would be compared to the canonical model. The samples would also need to be constrained in origin and time of formation. The Mn–Cr system would provide an additional validation of SLR dating, and Pb–Pb would be used as an absolute chronometer. Oxygen isotopes (^{16}O , ^{17}O , ^{18}O) would be measured to confirm the outer solar system origin of the

Table 1
List of Radionuclide Systems That Are of Interest to This Mission

System	Relevant Isotopic Ratios
Al–Mg	$^{26}\text{Mg}/^{24}\text{Mg}$, $^{26}\text{Mg}/^{25}\text{Mg}$, $^{27}\text{Al}/^{24}\text{Mg}$, and $^{26}\text{Al}/^{27}\text{Al}$
Mn–Cr	$^{52}\text{Cr}/^{50}\text{Cr}$, $^{53}\text{Cr}/^{52}\text{Cr}$, $^{54}\text{Cr}/^{52}\text{Cr}$, $^{52}\text{Mn}/^{52}\text{Cr}$, and $^{53}\text{Mn}/^{55}\text{Mn}$
Pb–Pb (U corrected)	$^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{206}\text{Pb}$, $^{207}\text{Pb}/^{235}\text{U}$, and $^{206}\text{Pb}/^{238}\text{U}$

comet material and distinguish it from other material picked up owing to radial mixing in the disk. Table 1 summarizes the ratios of measured mass-to-charge (m/z) signals for isotopes of interest.

2.3. Objective 2: Determine Whether Volatiles Were Predominantly Delivered to Earth via an Early Bombardment of 67P-like Comets

Water constitutes a fundamental ingredient to maintain habitable conditions for life as we know it. The source of the abundance of water on Earth’s surface remains a matter of active debate given that Earth formed in the inner solar system, a relatively dry place depleted in volatiles. Current explanations of inner solar system water and other volatiles include local enstatite chondrite parent bodies (L. Piani et al. 2020), carbonaceous chondrite parent bodies (B. Marty 2012), and/or delivery from comets formed in the outer solar system (A. Morbidelli et al. 2000). This objective would answer the question of the role that 67P-like comets played in the delivery of water and other volatiles to Earth’s atmosphere and interior.

Stable isotopes provide tracers for the origin of water and volatiles on Earth. The D/H (deuterium-to-hydrogen) ratio roughly corresponds to the formation location of water-bearing bodies in the solar system (A. E. Saal et al. 2013) as seen in Figure 3. Fractionation models typically indicate an increase in D/H with formation distance from the Sun (e.g., A. Drouart et al. 1999). In addition to water, the fractionation of stable isotopes of nitrogen ($^{15}\text{N}/^{14}\text{N}$) and noble gases provide an additional inherited constraint to the origin of volatiles currently found in Earth’s atmosphere.

Present D/H evidence points to different conclusions with regard to the role of comets in delivering water to Earth (Figure 3). The coma of comet Hartley 2 indicates a D/H similar to Earth’s oceans (P. Hartogh et al. 2011), while the coma of comet 67P indicates a D/H threefold enrichment compared to Earth’s oceans (K. Altwegg et al. 2015). A high D/H variability has been observed among JFCs (T. Albertsson et al. 2014; D. Bockelée-Morvan et al. 2015; C. Lécuyer et al. 2017), which has been attributed to differences in formation location. The consistent D/H ratio of the coma of comet 67P supports this interpretation (D. R. Müller et al. 2022). However, recent observations and modeling suggest that differences in observation time, instrumentation, and/or active surface area may also affect observed D/H (L. Paganini et al. 2017; D. C. Lis et al. 2019). Additionally, comets could consist of material formed at multiple locations (M. Fulle 2021). A comparison of water D/H measurements between the coma and surface could provide a useful perspective on these difficulties, but no sample from a comet surface has ever been analyzed for volatile isotopic ratios. The proposed sampling of

the surface of 67P would provide a significantly less modified measurement of the genetic imprint of cometary water than existing observations. This returned surface sample would thus produce the first ground calibration of water D/H measurements obtained from cometary comas and meaningfully constrain how chemical processes in the coma can fractionate volatiles in the entire comet population.

Contemporary comet compositions include numerous other volatile species trapped within water and/or carbon dioxide ice, suggesting that cometary delivery of water to the early Earth would have also resulted in delivery of other volatile species. Like H-containing species, isotopic ratios of other elements found in Earth’s oceans and atmosphere can hint at volatile origins. Remote-sensing measurements indicate a systemic comet enrichment in $^{15}\text{N}/^{14}\text{N}$ compared to Earth values (B. Marty 2012). The species accessible to remote observations are typically limited to cyanide (CN) and hydrogen cyanide (HCN) (E. Jehin et al. 2009; J. Manfroid et al. 2009; B. Marty 2012), with only a minority of studies indirectly sampling ammonia (NH_3) and diatomic nitrogen (N_2). The latter volatile species are of greater importance to the composition of Earth’s atmosphere and are not required to be in isotopic equilibrium with CN and HCN. Current ammonia observations in comets come from the related photodissociation product NH_2 (P. Rousselot et al. 2013; Y. Shinnaka et al. 2016) because of the difficulty of observing NH_3 directly (D. Bockelée-Morvan et al. 2016). The proposed sampling of the surface of 67P would provide the first opportunity to measure ammonia and molecular nitrogen from the comet’s surface, complementing and extending earlier remote-sensing and coma constraints (K. Altwegg et al. 2019). The two selected nitrogen species constitute major components of Earth’s atmosphere and were chosen because they have not yet been directly sampled on a comet surface. Surface cometary $^{15}\text{N}/^{14}\text{N}$ ratios may be more similar to those of Earth than those measured from coma species, or they may be consistent with coma measurements.

Noble gases react very rarely, and stable isotopes do not change atomic mass, making noble gas isotopic ratios stable over the billions of years since the solar system formed. Earth’s isotopic ratios (M. Ozima & F. A. Podosek 2002) differ from those of the solar wind as measured by the Genesis mission (A. Meshik et al. 2014) and from those measured in chondrites (H. Busemann et al. 2000). Heavier isotopes, such as ^{136}Xe and ^{86}Kr , are more abundant on Earth than in the solar wind (A. Meshik et al. 2014). Earth’s xenon isotopic ratio also differs from the proposed abundance of xenon in the primordial solar system (R. O. Pepin 2000). Multiple isotopes of argon, krypton, and xenon were all detected in the coma of 67P by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis double-focus magnetic mass spectrometer (ROSINA DFMS) on Rosetta (H. Balsiger et al. 2015), and the isotopic ratios of both krypton and xenon showed marked differences from all other isotopic ratios measured elsewhere in the solar system. The large error in the argon isotopic ratio measurement taken by ROSINA resulted in an average ratio consistent with either Earth or solar wind isotopic abundances (H. Balsiger et al. 2015). If measurements from the coma of 67P are representative of surface samples, this comet has isotopic abundances that differ from every other measured object in the solar system. Noble gas isotopes would be studied in Gelato’s returned samples because their isotopic ratios between

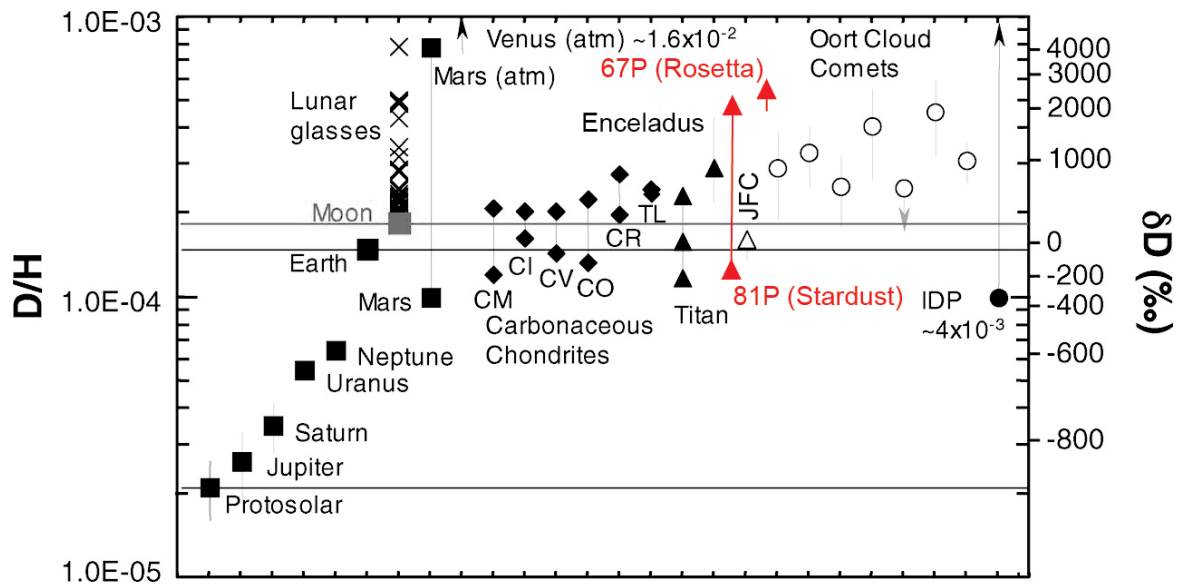


Figure 3. D/H ratios of different celestial bodies found in the solar system. The figure has been modified from A. E. Saal et al. (2013) with data from K. D. McKeegan et al. (2006) (Stardust) and K. Altwegg et al. (2015) (Rosetta). Other relevant values not shown include Rosetta’s measurement of 67P’s coma dust particles (J. Paquette et al. 2021). Also not shown are the additional cometary coma D/H measurements made since Rosetta, including those of 46P/Wirtanen (D. C. Lis et al. 2019), C/2014 Q2 (Lovejoy) (N. Biver et al. 2016; L. Paganini et al. 2017), and C/2012 F6 (Lemmon) (N. Biver et al. 2016), as well as a revised estimate for C/1996B2 Hyakutake (D. C. Lis et al. 2019).

isotopologues show the largest differences between Earth and other solar system bodies, and they can be directly compared with coma data collected by ROSINA (B. Marty et al. 2017; M. Rubin et al. 2018).

Volatiles on a comet surface are not static: they can interact with each other in a number of ways, including ways that could modify isotopic ratios. Hydrogen and deuterium atoms can move between water molecules, or between water and other molecules, and these isotope exchange reactions occur at an appreciable rate in the comet surface temperature range (T. Lamberts et al. 2015). Isotope exchange affects both coma and surface measurements, but mass-dependent sublimation only impacts coma measurements (C. Lécuyer et al. 2017; L. R. Smith et al. 2021).

67P-like comets may have played a predominant role, a minor role, or a negligible role in delivering volatiles to Earth. If they were a major source of Earth’s volatiles, the isotopic ratios listed in Table 2 would resemble those of Earth and contrast with Rosetta’s coma measurements. If they played a minor role, the isotopic ratios would differ from those of Earth but match coma measurements, and if they played a negligible role, then surface samples would have ratios that match neither Earth nor coma measurements.

2.3.1. Sample Requirements

Water is one of the most abundant species present in a comet, and water ice can trap other molecules (M. Choukroun et al. 2020). ROSINA data suggested that volatiles like N_2 and noble gases are trapped in CO_2 ice, so both water and carbon dioxide ice must be present in the area of the comet to be sampled (M. Rubin et al. 2018, 2023, Appendix A). This requires that the sampling location have surface ice rather than solely a meters-thick layer of regolith (H. Boehnhardt et al. 2017). The SRC must be hermetically sealed to prevent sublimating volatiles from escaping, since loss of species after mass-dependent sublimation would alter measured isotope

Table 2
List of Isotopes and Molecules Prioritized for Gelato Sample Analysis

Element	Relevant Isotopic Ratios	Relevant Species
H	D/H (δD)	H_2O
N	$^{14}N/^{15}N$	NH_3 , N_2
Ar	$^{36}Ar/^{38}Ar$	...
Kr	$^{82}Kr/^{86}Kr$, $^{84}Kr/^{86}Kr$	...
Xe	$^{128}Xe/^{132}Xe$, $^{136}Xe/^{132}Xe$	...

ratios. Note that the sample is degassed first and the gases are collected separately. Fulfilling this objective requires differentiating between the isotopes of noble gases using a ground-based mass spectrometer with sufficient sensitivity and resolution. Ground-based mass spectrometers can be fine-tuned to specific elements and isotopologues and measure their relative abundances at very low concentrations to a precision not possible with the best flight-ready mass spectrometers while also minimizing the presence of confounding species to a greater degree than flight-ready instruments. Additionally, the weight of flying a precise mass spectrometer would quickly add to the complexity, cost, mass, and power requirements of a mission. Therefore, a sample return mission is ideal for measuring these isotopic ratios to high precision. Gas chromatography–mass spectrometry and isotope ratio mass spectrometry (GC-MS/IRMS) would be used for D/H and nitrogen isotopic measurements, and gas-specific noble gas spectrometers would be used for noble gas isotopic measurements (e.g., J. H. Reynolds 1956; C. Hohenberg 1980 and S. Crowther et al. 2008). These methods are destructive. Masses needed are based on ROSINA estimates of abundances with respect to water (J. Crovisier et al. 2004; B. Marty 2012; L. Le Roy et al. 2015; B. Marty et al. 2017; M. Rubin et al. 2018). Noble gas species are the least abundant of the

considered species, and ^{136}Xe in particular drives the mass requirement. We determined a mass requirement of 0.118 g for Objective 2, which assumes a scenario of 1:10 ice:rock ratio based on the most conservative estimates of the bulk composition of the nucleus (M. Choukroun et al. 2020) and includes a guideline of 10 trials, an order-of-magnitude mass margin, and a storage allocation of 75%.

2.4. Objective 3: Determine Whether Comet 67P Is Host to Biologically Relevant Molecules and, If So, Whether They Formed in Presolar Interstellar Environments, the Protoplanetary Disk, or as a Consequence of Parent-body Processes

Due to biological and geological activity, there is no pristine rock record preserving the organic geochemistry of the early Earth prior to the origins of life. Astromaterials, having captured a snapshot of the organic chemistry in astrophysical environments, provide a mechanism for testing laboratory-based hypotheses and confirming the availability of organic compounds for origins of life chemistry (A. S. Burton et al. 2012). Indeed, studies of carbon-rich meteorites (i.e., carbonaceous chondrites) have shown that the biological building blocks for proteins (amino acids, AA), nucleic acids (sugars, N-heterocycles), and lipids (hydroxy acids), as well as a wide range of metabolites (e.g., ketoacids), could have been delivered throughout the solar system (A. S. Burton et al. 2012; G. Cooper et al. 2018; Z. Martins 2018; Y. Furukawa et al. 2019; J. C. Aponte et al. 2020; Y. Oba et al. 2022). Studies have also shown that carbonaceous chondrites (CCs) possess some amino acids and sugar derivatives with enantiomeric excess (EE) consistent with biology (D-sugar derivatives, L-amino acids) (G. Cooper & A. C. Rios 2016; A. S. Burton & E. L. Berger 2018). As meteorites are inevitably exposed to terrestrial life and weathering during their fall, they will have experienced different degrees of biological contamination and alteration that may impact their organic content (L. D. Tunney et al. 2020). Sample return from carbonaceous asteroids by Japan Aerospace Exploration Agency's (JAXA) Hayabusa2 and NASA's Origins, Spectral Interpretation, Resource Identification, and Security—Regolith Explorer (OSIRIS-REx) missions enable the confirmation of an abiotic origin for biologically relevant compounds (Y. Oba et al. 2023; E. T. Parker et al. 2023). However, asteroids endured a wide range of parent-body processing, which may have severely altered the original organic material, obfuscating the origins and chemical history of these compounds (C. D. Herd et al. 2011; C. O. Alexander et al. 2017).

Comets possess the oldest and least modified organic material available in the solar system (Z. Martins et al. 2020). Previous missions to comets have confirmed that they are proportionally enriched in organic carbon compared to asteroids (A. Bardyn et al. 2017; C. Potisil et al. 2022). Although there have been organic analyses of cometary samples returned from NASA's Stardust mission (J. E. Elsila et al. 2009; K. Altwegg et al. 2016), these samples were captured within the comet's coma; they are not likely representative of the nucleus's organic content, since most volatile compounds are preferentially lost or significantly reprocessed during collection (S. A. Sandford et al. 2006; J. E. Elsila et al. 2009). This is demonstrated in Figure 4, which shows that the ^{13}C versus ^{15}N composition of insoluble organic matter (IOM) (as opposed

to soluble organic matter (SOM)) on particles from comet 81P/Wild 2 collected by Stardust reflects substantially altered materials. Returning samples from the cometary nucleus would, unlike Stardust, provide sufficient volumes of less modified organic material for analyses requiring larger volumes of mass (e.g., compound-specific isotopic analyses).

Comets possess an abundance of organic matter predicted to have been generated from (Hypothesis 1 (H1)) irradiation of ices (e.g., by ultraviolet light (UV), X-rays, electrons, etc.) within the ISM or outer solar nebula, (Hypothesis 2 (H2)) high-temperature gas-phase reactions within the inner solar nebula (e.g., Fischer–Tropsch-type (FTT) synthesis), or (Hypothesis 3 (H3)) parent-body processes. Laboratory work has shown that biologically relevant molecules including amino acids, hydroxy acids, nucleobases, and sugars can form by all three processes (M. P. Callahan et al. 2011; A. S. Burton et al. 2012; Z. Martins et al. 2013; T. M. McCollom 2013a; Y. Oba et al. 2020; S. A. Sandford et al. 2020). Determining the origin of biologically relevant compounds within comets would (1) confirm an abiotic origin for these compounds, (2) reveal the relative importance of comets versus asteroids for prebiotic chemistry, and (3) elucidate whether endogenous geochemistry (e.g., early Earth) could have productively contributed to origins of life chemistry. Physical parameters that can be used to determine the origin of organic materials are summarized in Figures 2 and 4 and described in detail in the succeeding paragraphs.

H1 (irradiation of ices within the ISM or outer solar nebula). Organics generated under these conditions would have formed early in the comet's history and would be more abundant in comets than meteorites stemming from even the least altered asteroids. Irradiation under these cold environments produces organic matter with large D and ^{15}N isotopic anomalies (C. O. Alexander et al. 2017). If H1 is true, this would suggest that cold astrophysical environments birth not only stars but also the organic building blocks of life. Consequently, comets, which host less modified organic matter than asteroids, may have contributed more to origins of life processes on other worlds.

H2 (Fischer–Tropsch-type chemistry within the inner solar nebula). Although comets formed past the snow line, mixing of the protoplanetary disk could have led to the accumulation of inner solar materials within the cometary nucleus (F. Kemper et al. 2004; C. Lisse et al. 2006). Organics formed in the inner solar nebula would have been dominated by gas-phase FTT chemistry that is facilitated by metal grains (e.g., Fe, Ni) (J. A. Nuth et al. 2020). The resulting organics are predicted to be isotopically depleted compared to organics produced in cold dense molecular clouds, and moreover, FTT chemistry in and of itself preferably incorporates isotopically light elements (T. M. McCollom 2013b). As this chemistry would have occurred prior to comet formation, organics formed within the inner solar nebula should be more abundant within comets than severely altered asteroids; however, less altered asteroids may contain more of these organics, as they would have accreted more inner solar nebula materials than comets. Overall, this hypothesis requires hot gaseous reactions that were likely more prevalent in the inner solar system during planetary accretion than after planetary formation and the subsequent formation of cool oceans that would have poisoned these reactions. Thus, if true, H2 would suggest that

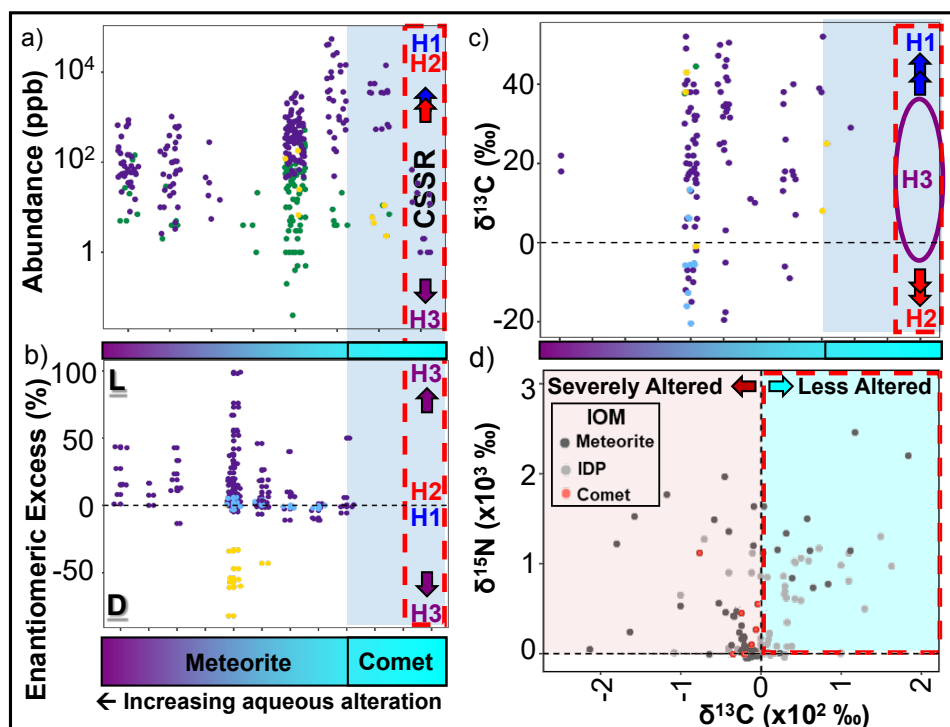


Figure 4. A compilation of organic data (amino acids (purple), N-heterocycles (green), sugars/sugar acids (yellow), and hydroxy acids (blue)) from meteorites, comets, and interplanetary dust particles (IDPs) that would be used to help evaluate the origin of biologically relevant organic molecules (hypotheses 1, 2, or 3 (i.e., H1, H2, H3)) on comet 67P. The arrows point in the direction the organics in question would plot if H1–H3 were true. From right to left, data are plotted from less altered materials (e.g., IDPs) to more altered meteorites (up to C11). (a) Abundance of organic compounds plotted on log scale. Amino acids are generally much more abundant than N-heterocycles and sugars. (b) EE of amino acids (L-enriched) and sugar derivatives (D-enriched). (c) $\delta^{13}\text{C}$ of organic compounds, predominately AAs. (d) $\delta^{15}\text{N}$ vs. $\delta^{13}\text{C}$ of IOM, used to determine how relatively altered a particular sample is. Note that the samples collected from Stardust (labeled comet) plot with other severely altered materials. Data acquired from C. O. Alexander et al. (2007), B. T. De Gregorio et al. (2010, 2013), Y. Furukawa et al. (2019), D. Bockelée-Morvan et al. (2008), P. Rousselot et al. (2014), J. Manfroid et al. (2009), S. Wyckoff et al. (2000), Z. Martins et al. (2007), J. C. Aponte et al. (2020), H. Busemann et al. (2009), J. E. Elsila et al. (2012), C. Floss et al. (2006, 2014), K. D. McKeegan et al. (2006), G. Matrajt et al. (2008), A. S. Burton et al. (2013), G. Cooper & A. C. Rios (2016), J. R. Cronin & S. Pizzarello (1997), D. P. Glavin & J. P. Dworkin (2009), D. P. Glavin et al. (2006, 2008, 2010, 2012, 2021), S. Pizzarello & W. Holmes (2009), S. Pizzarello et al. (2003, 2006, 2008, 2010, 2012), O. Botta et al. (2002), K. E. Smith et al. (2014), and P. G. Stoks & A. W. Schwartz (1979).

asteroids were more important than both comets and endogenous planetary processes for origins of life chemistry.

H3 (parent-body processes). Biologically relevant organics may have been generated as a result of aqueous/thermal/shock processes altering organic precursors present in the cometary body. Evidence suggestive of aqueous alteration was found by Deep Impact, which observed minerals diagnostic of aqueous processing (i.e., phyllosilicates and carbonates) on the comet Tempel 1 (C. Lisse et al. 2006), whereas Rosetta-collected dust from 67P showed no such signs (A. Bardyn et al. 2017). Hydrothermal and shock processing could be triggered during cometary accretion or by impact events; low-temperature aqueous alteration could be initiated when a comet approaches perihelion should it warm sufficiently to trigger melting (C. Lisse et al. 2006). Molecules resulting from parent-body alteration of organic materials generated within the ISM, solar nebula, or the comet itself are predicted to have isotopic ratios representative of source reservoir mixing. The abundance of organic matter generated via parent-body processes is expected to be lower within less modified comets compared to aqueously and/or thermally altered asteroids. Should H3 be found true, this would suggest that aqueous and/or thermal processing, which may be more prevalent on planetary bodies where there is ongoing endogenous geochemistry, is critical toward the formation of biologically relevant materials.

2.4.1. Sample Requirements

Organic trends can be overprinted owing to organic degradation or organic reaction if acquired samples are heated to temperatures beyond those experienced at the comet's surface. Generally, the lower the temperature at which the samples are kept, the better; however, this comes at an increasing cost and burden to the mission. Rather, the mission requires that the samples never be heated beyond surface temperatures that were widespread at the comet for long periods of time. The surface temperatures of the comet measured by Rosetta ranged from -123°C to -43°C during pre-perihelion (F. Tosi et al. 2019); during perihelion, the comet was certainly warmer, but due to surface outbursts, Rosetta could not land during this period. Recent thermal models suggest that the maximum temperatures reached at perihelion in the northern hemisphere (-63°C to $+26^{\circ}\text{C}$) are relatively low compared to the maximum temperature range at the equator ($+26^{\circ}\text{C}$ to $+77^{\circ}\text{C}$) and the southern hemisphere ($+77^{\circ}\text{C}$ to $+126^{\circ}\text{C}$) (O. Groussin et al. 2025), with most of the northern hemisphere and most of the equator having maximum temperatures of $\sim 26^{\circ}\text{C}$. The sampling site would be determined during the mission, but it is possible that the sample that would be collected never experienced temperatures greater than $+26^{\circ}\text{C}$. Consequently, it was decided to restrict the sample temperature requirement to $<+25^{\circ}\text{C}$. Table 3 describes the rationale for the sample mass

Table 3
Rationale for Mass Requirements for Objective 3

Compound	Half-life in Water	Percentage Left after 1 hr	Low-end Abundance (ppb)	Limit of quantification (pg)	Mass per Analysis (g)	Spare (%) (%)	No. Tests	Mass per Investigation (g)
<i>N</i> -heterocycles	100°C pH 5–10 >19 days [1]	99.9	0.1 [6]	10	0.1	50	10	1.5
Amino acids racemization	100°C >320 days [2] ~half-life for degradation [3]	~100	1 [5]	10	0.01	50	10	0.15
Sugars	100°C, pH 7.4 73 minutes [4] 60°C, pH 11 ~75 hr [4]	58.9 99.3	0.1 [6]	10	0.1	50	10	1.5
Hydroxy acids	...	...	1 [5]	10	0.01	50	10	0.15
Isotopic observables	...	...	ppm	μg	g			g
δD and δ ¹³ C for amino acids	...	...	5	5	0.1	50	10	1.5
δD and δ ¹³ C for hydroxy acids	...	...	5	5	0.1	50	10	1.5
δD, δ ¹³ C, δ ¹⁵ N, δ ¹⁸ O for IOM	...	...	use IOM extracted from SOM residue (6 g minimum for 10 replicates each)					

Note. Bracketed numbers correspond to references (1) M. Levy & S. L. Miller (1998), (2) S. L. Miller & A. Lazcano (1995), (3) J. Li & T. B. Brill (2003), (4) R. Larralde et al. (1995), (5) A. S. Burton et al. (2012), and (6) Y. Furukawa et al. (2019).

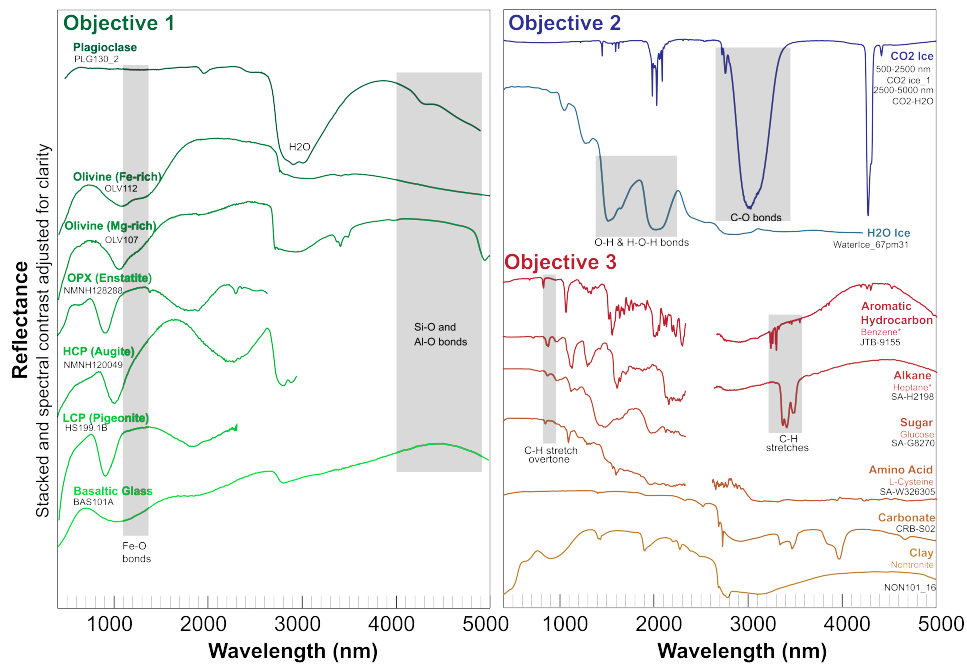


Figure 5. Laboratory spectra of minerals relevant to Objective 1 (left in green), Objective 2 (top right in blue), and Objective 3 (bottom right in red). Key spectral features for identification are noted in gray boxes and lines. Spectra are from United States Geological Survey (USGS) Spectral Library Version 7 (R. Kokaly et al. 2017), the University of Winnipeg’s Centre for Terrestrial and Planetary Exploration’s spectral database, the Solid Spectroscopy Hosting Architecture of Databases and Expertise (B. Schmitt et al. 2018), and the Cosmic Ice Laboratory (R. Hudson & M. Moore 1999).

requirement based on the sample maximum temperature requirement and earth-based laboratory analysis.

The nucleus surface will have experienced warmer temperatures and more chemical processing than deeper within. However, strategic sampling of the surface can ensure that samples collected have experienced minimal aqueous alteration (i.e., there are little to no phyllosilicates, carbonates, or magnetite). In addition to aqueous alteration, cometary surface material is exposed to irradiation from solar wind that removes volatiles and heteroatoms (HNOS) and aromatizes organic materials (low molecular weight $\rightarrow$ insoluble/aromatic organic materials) (L. Moroz et al. 2004). Given this, we would search for and sample from sites with minimal alteration by monitoring the following via thermal IR: $4.62\ \mu\text{m}$ (XCN feature), $6.8\ \mu\text{m}$, $15.2\ \mu\text{m}$ (triple-peak structure of the bending mode of CO_2) (M. Moore et al. 2001), bending modes affiliated with volatiles, and a strong absorption at $3.2\ \mu\text{m}$ that is predicted to be a mixture of semivolatile organic matter consisting of low molecular weight organics (E. Quirico et al. 2016).

3. Science Implementation

3.1. Hyperspectral Imager

Data from the hyperspectral imager on board Gelato would be used for mineral identification by acquiring visible to mid-infrared ($0.4\text{--}5.0\ \mu\text{m}$) spectral data. In this wavelength range, mineral identification relevant to our science objectives is possible through the absorptions caused by electronic processes in transition metals like $\text{Fe}^{2+/3+}$ and vibrational processes like the bending and stretching of metal–OH bonds and within water molecules commonly present in silicates, organics, and ices (e.g., G. R. Hunt 1977; R. N. Clark & T. L. Roush 1984; E. A. Cloutis & M. J. Gaffey 1991;

R. L. Klima et al. 2007; R. N. Clark et al. 2009; C. Laukamp et al. 2021) (Figure 5). The $3\ \text{nm}$ spectral resolution with a ground sampling distance (GSD) of $7.5\ \text{m}$ would allow for the identification of minerals required for all three science objectives. Moreover, the $65\ \text{m pixel}^{-1}$ spatial resolution can provide relative comparison of mineral distribution to morphological features of the comet surface.

Spectral data for Gelato have a minimum required signal-to-noise ratio (SNR) value of 400, sampling at least once every half hour, over an integration time of $2.12\ \text{s}$ to prevent oversaturation of captured images. This SNR value can provide a strong enough signal to illustrate plagioclase feldspar subtle spectral features (e.g., J. B. Adams & L. Goulaud 1978) while diminishing external influences (thermal emission from instrument, fluctuation in signal source, electronic noise, etc.), which would normally jeopardize the quality of the spectral data. Observations would be made when the surface is in direct illumination by the Sun. Ultimately, we require a GSD of $32.73\ \text{m pixel}^{-1}$ and spatial coverage of $>90\%$ of the cometary surface (including the use of previously acquired compositional data from Rosetta) to identify a sampling location that likely has compositions required for science closure as defined in our science objectives. See Table 4 for payload accommodation requirements. Additional details about the observations associated with each objective are included in Appendix A.

3.2. Three-color Pushbroom Camera

The three-color pushbroom camera would acquire high-resolution surface images. As part of Gelato’s instrument suite, it is designed to provide geomorphologic context to the mineralogic information provided by the hyperspectral imager. To do so, near-global ($>90\%$) image coverage would allow for robust geomorphologic characterization and ensure that the

Table 4
List of Payload Accommodation Requirements for the Five Different Instruments on Board Gelato

Payload Accommodation Requirement	Near-/Mid-IR Hyperspectral Imager	Three-color Pushbroom Camera	Sampling Camera (on BiBlade)	Descent Camera (x2)	BiBlade Sampling Arm
Current Best Estimate (CBE) mass (kg)	~33.0	~8.2	~0.58	~0.58	~25
CBE power (W)					
Peak	~49	~9.3	~10	~10	~30
Operating average	~46	~6.4	~10	~10	~0.05
Standby	~30	~2.5	~3	~3	0
CBE data rate (bps)	813	2819	$\sim 3.2 \times 10^7$	$\sim 3.2 \times 10^6$	0
Pointing					
Knowledge (arcsec 1/sigma)	6	10		10	
Control (arcsec 1/sigma)	30	50	N/A	50	N/A
Stability (arcsec/sec 1/sigma)	8.5	20		20	
Viewing direction (body coordinates)	Nadir	Nadir	SRC	Nadir	Nadir
CBE dimensions (L × W × H in m)	$0.77 \times 0.57 \times 0.39$	$1.18 \times 0.27 \times 0.27$	$0.074 \times 0.088 \times 0.15$	$0.074 \times 0.088 \times 0.15$	$1.13 \times 0.4 \times 0.2$

sample site avoids obstacles while also targeting recently exposed materials. Color images would be used in conjunction with hyperspectral data to identify geomorphologic features consistent with the mapped composition to determine the best site for sample collection. The onboard camera provides broadband visible data with an SNR of 42 at a GSD of 0.225 m, meeting the requirements to resolve features that are <0.5 m. See Table 4 for payload accommodation requirements.

Specific geomorphologic units previously observed on 67P are indicative of a relatively primitive cometary surface (S. P. Birch et al. 2017). Units are broadly divided into “rough” and “smooth” terrains, where “rough” terrains are more likely to expose primitive surface materials (S. P. Birch et al. 2017; M. R. El-Maarry et al. 2019). Rough units include cliffs, talus deposits, bouldered plains, and mottled pit terrains, which have been previously mapped at 0.5 m pixel^{-1} spatial resolution (see Section 4.2). Based on previous compositional mapping by Rosetta, refractory materials relevant to Objective 1 are widespread on the surface of 67P (G. Filacchione et al. 2016) and are not restricted to a particular morphology. Ices and organic compositions relevant to Objectives 2 and 3, respectively, are observed in highest abundances at cliff terrains.

Between Rosetta’s hard landing in 2016 and Gelato’s planned arrival in 2038, 67P would experience three perihelia. Rosetta observed compositional and morphological changes during its perihelion observations (e.g., O. Groussin et al. 2015; D. Bockelée-Morvan et al. 2016; M. Ciarniello et al. 2016), so three perihelia would produce even more widespread changes. High-resolution surface images to detect these structural changes would enable selection of a sample site with minimal processing and reduced collection risk.

3.3. Sampling and Descent Cameras

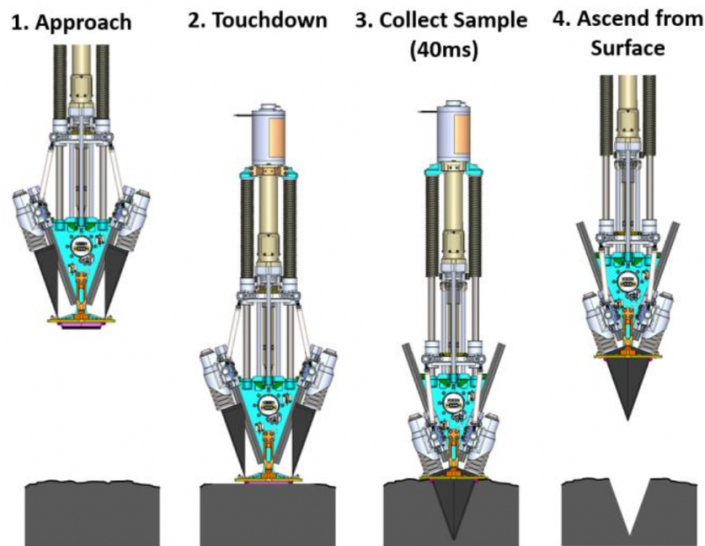
Gelato would also carry two descent cameras to be used during the sampling phase for targeting and optical navigation, as well as a sampling camera affixed to the BiBlade arm to confirm sample acquisition and storage. These additional cameras would be integrated into the control subsystem. Data collected from these cameras would not be necessary for

meeting science requirements. See Table 4 for payload accommodation requirements.

3.4. Sample Collection

The BiBlade sampling chain was selected for use as the comet surface sampler. The BiBlade uses a touch-and-go mission architecture and utilizes a two-shovel blade design that quickly fires into a surface, surrounds the sample, and retracts to remove and contain the sample (Figure 6(a)). The BiBlade has been validated to technology readiness level (TRL) 6 and can collect at least 250 g of material (more than the 133.25 g from science requirements), and based on ground testing, the probability of sample acquisition is high. The sampling operation itself occurs within a 40 ms window, with tests having been performed to ensure that no drastic temperature changes occur within the sample. Oblique strikes have been tested, and the blades are retractable, allowing for multiple sampling attempts if needed. However, Gelato would only store one sample. The BiBlade has been tested on material with a cone penetration resistance of up to 5 MPa (P. Backes et al. 2017) (Figure 6(b)), orders of magnitude greater than what is likely needed to penetrate the surface of 67P, which, based on studies of the dynamics of the Philae lander’s encounter with the surface (P. Heinisch et al. 2019; L. O’rourke et al. 2020), was measured to be 12 Pa.

Various methods may be used to verify the mass of the sample, including those that leverage the change in inertia of the spacecraft or the motion of the collection blades relative to the collection arm. Other tested sample verification techniques (P. Backes et al. 2014; R. Toda et al. 2016) require a separate measurement station that opens the head of the BiBlade slightly. Gelato would primarily rely on momentum-based methods for determining sample mass in addition to optical verification of acquisition through the use of the sample camera. Another alternative for sample verification is to measure the blade’s trajectory during sampling. While some of the tests related to this measurement technique have used non-TRL6 components, flight-qualified alternatives have been identified (P. Backes et al. 2014). As such, verification of



(a) Schematic of the BiBlade during its four stages of sample collection.



(b) Sample acquisition from a 5.2 MPa simulant block during penetration test.

Figure 6. BiBlade sampling chain. Images from P. Backes et al. (2017).

the system performance using such equivalents would be required if this verification approach were to be adopted.

3.5. Sample Return Capsule and Contamination Control

Detailed design of the SRC was outside the scope of this study. However, the science objectives and requirements rely on existing technologies used on current and previous sample return missions, including OSIRIS-REx, Hayabusa2, and the proposed CAESAR (A. G. Hayes et al. 2020) mission concept: post-sampling hermetic seal, sterilized stainless steel containment, and temperature control at $<25^{\circ}\text{C}$ to prevent organic alteration. Gelato would also require the extraction and separate storage of volatile species that is consistent with the SRC modified from Hayabusa2 for use with a cometary sample (D. Glavin et al. 2019). Once samples are collected, the SRC would be sealed and slowly heated to -30°C to promote desorption of volatiles that will then be trapped in a passively cooled gas containment system (D. Glavin et al. 2019). After gas transfer is complete, the gas containment system would be hermetically sealed and the sample containment system (like the Hayabusa2 and OSIRIS-REx SRCs) would be allowed to vent to space during the return cruise. The vent's filter would prevent particulate contamination but allow desorbed gases to escape, preventing the sample canister from overpressuring and/or allowing liquid water to form (J. Dworkin et al. 2018). The SRC would be hermetically sealed just before entering Earth's atmosphere to prevent terrestrial contamination and could be kept at temperatures $<25^{\circ}\text{C}$, although it has been demonstrated how the SRC could be kept at $<0^{\circ}\text{C}$ (D. Glavin et al. 2019). It was determined that keeping the samples below 25°C with volatiles stored separately would be adequate for preventing aqueous alteration that would compromise Gelato's science objectives. Future efforts to design the SRC in detail would need to ensure that the SRC could maintain a temperature $<25^{\circ}\text{C}$ throughout the return cruise. This would be accomplished by leveraging thermal models that predict temperature changes in the SRC components depending on the

configuration of the SRC on the spacecraft and the pointing direction of the spacecraft relative to the Sun during its return cruise to Earth. Given the temperature sensitivity of the sample, maintaining a record of the temperatures it experienced during the return to Earth would be essential, necessitating a temperature monitor similar to that used on the Hayabusa2 SRC (T. Yada et al. 2022).

Requirements for contamination management were modeled after the OSIRIS-REx contamination control strategy (J. Dworkin et al. 2018) and information from the Organic Contaminants Science Steering Groups (P. Mahaffy et al. 2004). The in-flight sample collection and storage components would be sterilized prior to launch according to previously established standards (J. Dworkin et al. 2018). Additionally, Gelato would document contamination acquired by the sampler head prior to launch up until the samples are stored for curation using witness plates strategically positioned on the sampler head and spacecraft assembly. Spacecraft sampling hardware should maintain a minimum 100 particulate requirement, nonvolatile residue level A/2 (500 ng cm^{-2}), $<180\text{ ng cm}^{-2}$ of amino acids, and $<180\text{ ng cm}^{-2}$ of hydrazine on the sampler head. Additionally, the spacecraft propellant would be sampled and analyzed prior to launch to ensure that the isotopic composition is well-known.

3.6. Sample Curation and Analysis

All samples acquired on NASA missions are delivered to, and processed by, the NASA Astromaterials Acquisition and Curation Office located at NASA's Johnson Space Center (JSC). Given the pre-Phase A nature of this study, a detailed plan for how samples would be collected and curated fell outside the project's scope. As such, we draw from the procedures established by OSIRIS-REx, which was also heavily interested in organic matter and thus required strict contamination controls and knowledge (K. Richter et al. 2023). These best practices exist for curation of refractory material, but handling of volatile-containing material would

require technological and methodological development. Discussion of the engineering constraints to minimize alteration of cryogenic samples can be found in recent reviews discussing curation of volatile-rich lunar samples (S. Noble et al. 2024; C. K. Shearer et al. 2024; D. Gilbertson et al. 2026). We thus describe in brief the sample collection and curation procedures established by OSIRIS-REx. Gelato's SRC would be released ~ 4 hr before atmospheric reentry and hermetically sealed to prevent oxidation, terrestrial contamination, and volatile loss as the SRC descends through the atmosphere. The target landing site would be the Utah Test and Training Range, which was the landing site for the SRCs of NASA's OSIRIS-REx, Stardust, and Genesis missions. Soil and air samples of the surrounding environment would be collected as part of the recovery procedures. Within 1–2 hr the SRC would be transported to an International Organization for Standardization (ISO) standard cleanroom, where it could be purged with ultrapure nitrogen gas and sealed to mitigate seepage of the terrestrial atmosphere into the SRC. From landing to processing at JSC the samples would be kept below $+25^{\circ}\text{C}$ to mitigate alteration. Once at JSC's ISO 7 cleanroom, the sample canister would be removed and taken to a cleanroom, where it would undergo preliminary examination (PE). The sample canister would be opened in nitrogen gloveboxes following JSC curation procedures (K. Richter et al. 2023). Within the JSC cleanroom, the samples would be stored in ultrapure nitrogen isolation chambers designed like gloveboxes, which, prior to receiving the samples, would be maintained at 10^{-6} torr vacuum to decontaminate, process, and store the received samples (D. White 1976; M. J. Calaway et al. 2014). For organic-rich samples, frequent microbial monitoring of the curation facility would be critical.

In the PE phase, samples would be weighed and then analyzed using nondestructive techniques to generate a comprehensive sample catalog for the community and a subsample, representative of the sample diversity, that would be preserved for long-term curation. Following the PE phase, samples would be distributed to the science team to address mission objectives within a 2 yr time frame. After this time period, the samples would be available through NASA JSC's Astromaterials Curation Office for community requests through a competitive process.

A bulk of the sample would be kept at room temperature in hermetically sealed containers infilled with an inert gas that has been isotopically characterized (so as not to inhibit isotopic measurements of noble gases; Section 2.3). Furthermore, at minimum 3.4 wt% of the 75% of sample reserved for long-term storage should be kept at -80°C in hermetically sealed containers filled with an inert gas. Assuming that 250 g is returned, 6.3 g would be frozen (enough to repeat all measurements from Objective 3). As chemical reaction rates generally double for every 10°C increase in temperature, freezing could have a substantial impact on inhibiting both biological and chemical alteration, including isotopic fractionation, oxidation, and volatile sorption. Moreover, previous studies have found that frozen samples not only sustained significantly more volatiles but also reduced organic degradation and contamination from the surrounding environment (C. D. Herd et al. 2016; K. Burgess et al. 2022). Having a portion of samples stored at cold storage also follows the recommendations for OSIRIS-REx (2.5 wt%) (L. Nittler 2023). Although the benefits of storing curated samples at

-20°C versus -80°C (or intermediate temperatures) have not been reported, the latter is preferable because microbial growth is more effectively inhibited, chemical reactions are further slowed, and -80°C better represents the comet's typical temperature outside perihelion. We therefore recommend long-term storage at -80°C .

Numerous ground-based analytical facilities would be required to satisfy the science goals of the Gelato mission. Objective 1 requires nanoscale secondary ion mass spectrometry (Nano-SIMS) and multicollector inductively coupled mass spectrometry (MC-ICP-MS) (Section 2.2). Objective 2 requires GC-MS/IRMS and noble gas mass spectrometry systems (Section 2.3). To address the multiple components of Objective 3, liquid chromatography–mass spectrometry (LC-MS), gas chromatography–mass spectrometry (GC-MS), gas chromatography–isotope ratio mass spectrometry (GC/IRMS), X-ray fluorescence spectroscopy (XRF) for coordinated analysis, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), Raman, Nano-SIMS, and two-step laser mass spectrometry (L2MS) are all necessary (Section 2.4, Figure 2). Ground-based instruments with the needed resolution already exist and have been described elsewhere (e.g., the OSIRIS-REx sample handling plan; D. S. Lauretta et al. 2023).

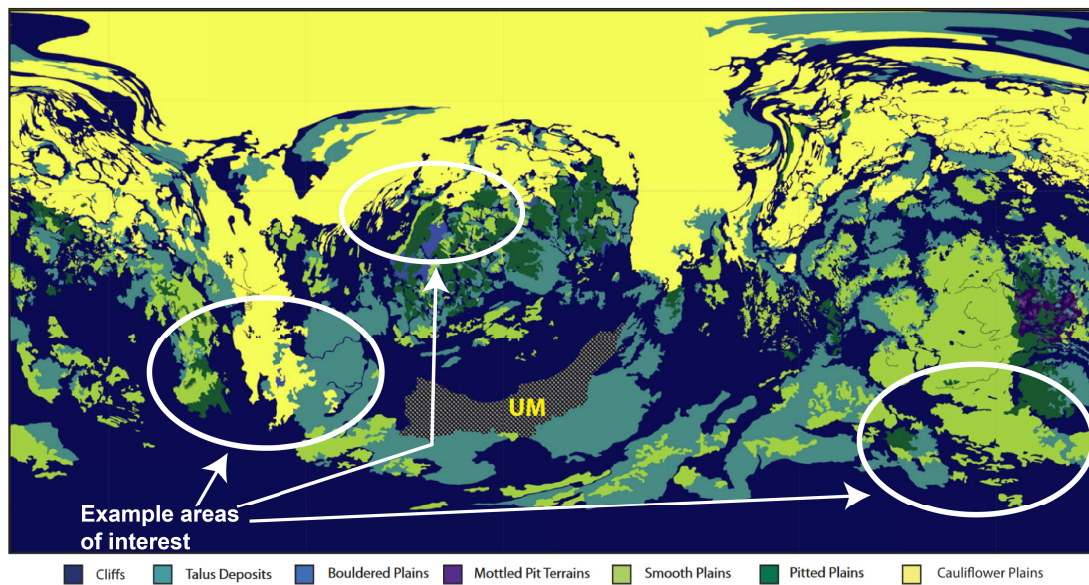
4. Mission Design

4.1. Comet Selection

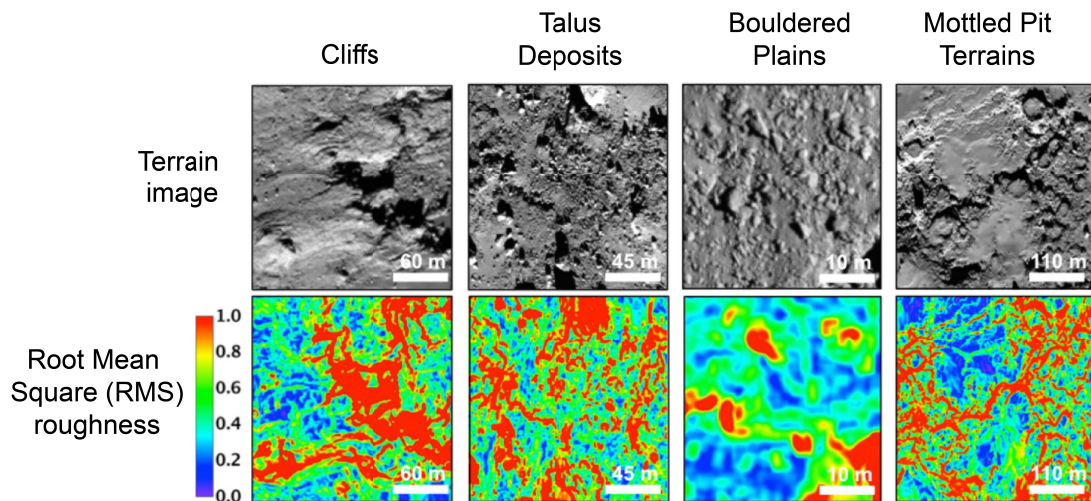
The Gelato mission would target Comet 67P/Churyumov–Gerasimenko (67P). 67P is currently the best-studied JFC, due to the success of the Rosetta mission. Despite this fact, at Gelato's arrival in 2038, 67P would experience three perihelia since Rosetta's exploration, spurring a variety of surface modifications due to thermal cycling, including but not limited to activity from jets of gas and dust, as well as particle redistribution across the surface. In addition, recent thermal modeling (O. Groussin et al. 2025) suggests that the distribution of surface temperatures impacts thermal processing of the interior. Thus, time has rendered 67P an appreciably different comet from the one Rosetta visited. As such, in spite of Gelato planning a revisit to 67P, thorough mapping of the surface morphology and composition would be necessary to characterize the surface and find a suitable sample location. That being said, the availability of high-resolution images covering the entire nucleus ($\sim 1\text{--}2\text{ m pixel}^{-1}$) (S. P. Birch et al. 2017), as well as spectral data at a spatial resolution ranging from ~ 2 to 25 m pixel^{-1} (G. Filacchione et al. 2016), would allow Gelato to detect changes in the organic and mineralogical content since Rosetta visited, including at candidate sample collection sites, and would thus yield insight into the nature of comet evolution. Details about the comet selection process and choice of backup comet are included in Appendix B.

4.2. Sample Site Selection

Comets are dynamic bodies where outgassing has been shown to change the surface composition over a matter of months (D. Bockelée-Morvan et al. 2016) and transport materials large distances across the surface (H. U. Keller et al. 2017; M. Hoang et al. 2019). The changing illumination and thermal conditions during elliptical orbits result in chemical and thermal alteration of surface layers (A. Gkotsinas et al. 2022). The Rosetta mission observed complex terrain morphologies,



(a) Geomorphological map of 67P showing the types of terrains identified at the surface which include cliffs (dark blue), talus deposits (teal), boulderated plains (blue), mottled pit terrains (purple), smooth plains (light green), pitted plains (dark green), and cauliflower plains (yellow). There is an unmapped region (UM) due to shadows in available imagery. Figure modified from Figure 7 in Birch et al. (2017).



(b) Regions of the comet surface that are likely to expose less modified material. Top images are geomorphologic mapping units based on Rosetta imagery and bottom images are root mean squared (RMS) roughness maps. Figure modified from Figure 8 in Birch et al. (2017)

Figure 7. Geomorphology of 67P used to identify potential sampling locations.

including pitted terrains (J.-B. Vincent et al. 2015), fractures (M. R. El-Maarry et al. 2019), boulders (M. Pajola et al. 2015), and slump deposits produced by cliff collapse (M. Pajola et al. 2017). These processes are indicative of a surface that has experienced sustained modification that may not reflect the bulk characteristics of the interior of the cometary nucleus.

Among these terrain morphologies, however, are morphological indicators of freshly exposed materials (S. P. Birch et al. 2017). Rougher terrains, like the cliffs, talus deposits, boulderated plains, and mottled pit terrains, are expected to expose less modified material (Figure 7(a)). Rosetta also detected spectral variability indicating heterogeneous surface composition (G. Filacchione et al. 2016). Surface regions were

qualitatively determined to be less modified if there was water ice present, based on the $2\ \mu\text{m}$ band depth, as water ice sublimates and disappears from the surface when the comet is active (G. Filacchione et al. 2016).

An extended mapping phase would highlight compositional and/or morphological changes that have occurred between the arrivals of Rosetta and Gelato. This phase would allow Gelato to target locations that not only appear to be recently exposed but also show evidence of sustained erosion such as those identified by H. U. Keller et al. (2017) so as to minimize sampling of recent fallback material. Additionally, these observations would give context regarding how similar the chosen sample area is to the rest of the mapped surface.

Although thermal modeling suggests a diurnal skin depth on the order of several centimeters (S. Gulkis et al. 2015; S. Höfner et al. 2017), recent work suggests a seasonal skin depth closer to 1 m (O. Groussin et al. 2025) (deeper than the BiBlade mechanism can surpass), underscoring the need for a mapping/surface characterization phase to identify recently exposed materials.

Sample site selection may be driven by illumination conditions that would permit autonomous optical navigation to the site. While Figure 7(a) highlights example regions that are compelling from a geomorphological and compositional perspective, the extended mapping phase would ensure the selection of sites with sufficient illumination during the critical portions of its 6 hr collection window.

4.3. Concept of Operations

The four primary phases of spaceflight operations for this mission are spacecraft outbound cruise, target rendezvous, inbound cruise, and rendezvous with Earth. Assuming the baseline mission schedule, Gelato would launch in 2033 (Figure 1) and perform an Earth gravity assist during the 6 yr outbound cruise to comet 67P. Instrument calibration and testing would continue during this phase, and station-keeping corrections would be performed as necessary.

The Rosetta mission experienced several challenges during near-perihelion spacecraft operations when 67P was active (M. Pérez-Ayúcar et al. 2018; N. Attree et al. 2019), including but not limited to particulates obscuring star tracker navigation solutions and dust jet emission (C. Lisse et al. 2022). While these challenges are surmountable through improved star trackers, higher-fidelity noise rejection algorithms, attitude control systems that rely more on gyroscopic measurements, and planning that avoids jets identified during the mapping phases (C. Lisse et al. 2022), Gelato would sample the comet at a comet–Sun distance of >2.5 au in order to buy-down risk involved with the sampling maneuvers. Reconnaissance and sampling cannot be separated by a perihelion, due to the extent of compositional and morphological changes that occur during perihelion (e.g., O. Groussin et al. 2015; D. Bockelée-Morvan et al. 2016; M. Ciarniello et al. 2016). Therefore, Gelato would arrive at 67P shortly after aphelion and depart before perihelion (Figure 8(a)). The spacecraft would experience its maximum spacecraft–Earth distance of 6.73 au approximately 4 yr after launch and would reach its aphelion roughly 1 yr later.

The most critical phase of the mission is the reconnaissance phase, as it informs the choice of sample site. During this 2 yr phase, Gelato would perform numerous flight operations along with orbital changes dependent on sample site location (Section 4.2). The first year would consist of two orbital phases, HAMO and LAMO. The HAMO campaign would consist of 8 months allocated to the selection and context characterization of up to four candidate sample sites. During this time, the comet nucleus would be analyzed at an orbital radius of 25 km, using the scientific payload to detect changes in the comet’s morphology and composition compared to data collected by the Rosetta mission. HAMO operations would be performed with a high duty cycle where active data collection would occur for 90% of the time, with the remaining time scheduled for telecommunications. The LAMO observations would occur over the remaining 4 months of the reconnaissance phase and be dedicated to detailed compositional/

morphological characterization and hazard analysis of the candidate sample sites to select a final sampling location. LAMO operations would be performed at an orbital radius of 7 km and have a slightly lower instrument duty cycle necessitated by increased telecommunications for orbital corrections proximal to the comet surface. The selection of spacecraft orbital characteristics was limited in this analysis to the orbiting distance needed to ensure the closure of science requirements. However, the problem of spacecraft dynamics and control in the complex dynamical environment presented by small bodies is a well-studied problem (D. Scheeres et al. 1995; D. J. Scheeres & F. Marzari 2002; D. Scheeres 2012), and the impacts of comet-specific dynamics encountered at 67P, including outgassing (S. M. Byram et al. 2007) and dust outbursts (U. Fink et al. 2021), are similarly modeled. Thus, the literature may be leveraged to further refine Gelato’s trajectory in subsequent analyses. Although telecommunications may be interrupted during periods of eclipse, these occultations would be brief and minimally disruptive given the velocity of the spacecraft, the inclination of its orbit, and the angular size of the target body. Following LAMO phase completion and selection of the final sample site, two sampling rehearsals would be conducted, followed by the sample collection (Figure 8(b)), over the course of 12 months.

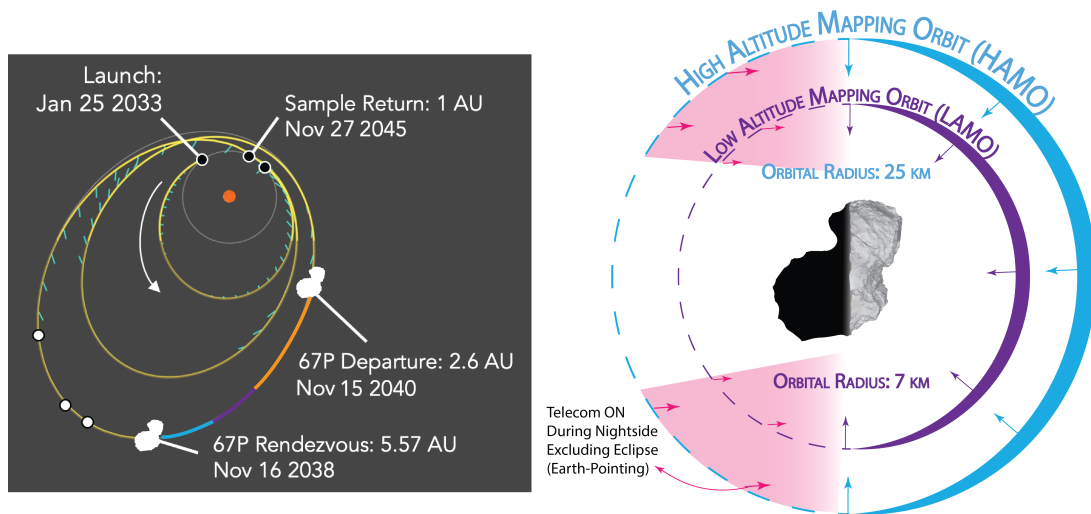
Assuming the baseline mission timeline, the return cruise would begin during 2040 at 2.6 au and would be projected to last 5 yr, after which the sample would be returned to Earth and retrieved from the SRC to undergo curation procedures (Section 3.6). Excluding post-return sample curation and analysis, this results in a nominal mission duration of 13 yr from launch to Earth return.

5. Mission Implementation

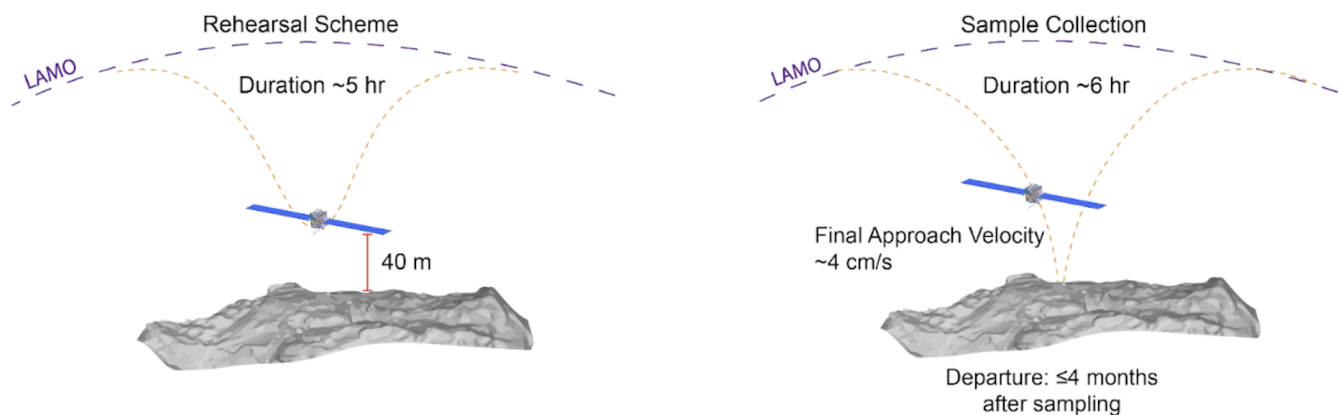
5.1. New Frontiers Requirements

The Gelato mission concept was developed to satisfy the requirements of the NF4 AO. The NF4 cost cap was \$850 million in FY2015 US dollars, or equivalently \$1.05 billion in FY2025. The NF4 PI–Managed Mission Cost (PI-MMC) for sample return missions also includes construction of curation facilities and the curation and distribution of sample materials through 2 yr following sample return. Mission costs were estimated using the Team X Cost Model internally developed at JPL, a quasi-grassroots model that references databases of historic workforce costs and historic mission costs, as well as current pricing for spacecraft components. The Team X Cost Model is maintained by JPL engineers and is verified every 5 yr against the actual costs of new space missions. The Gelato cost estimate was also verified against the actual costs associated with OSIRIS-REx, and its modeled costs were found to be within 30% of the OSIRIS-REx actual costs.

A total of 13% of the cost cap, or \$136.5 million in FY25, was allocated to the science payload based on the costs attributed to each element of previous New Frontiers missions. Half of that portion was then allocated for the sample collection mechanism, leaving \$68 million FY25 for science instrumentation. Scientific payload instrument expenses were estimated based on the cost of their closest analog with spaceflight heritage. The Astromaterials Research and Exploration Science Division at NASA’s Johnson Space Center was consulted to estimate costs associated with sample storage facility construction and curation based on our sample



(a) Spacecraft trajectory from launch to sample return (**left**) including an Earth gravity assist and rendezvous with 67P post aphelion. Concept of operations (**right**) with HAMO/LAMO configurations.



(b) Sampling rehearsal maneuvers (**left**) performed twice prior to sample collection maneuvers (**right**) during the final year of orbital operations.

Figure 8. Spacecraft trajectory, orbital, and sampling operations.

storage requirements (Section 3.6); these estimates are comparable to the New Frontiers 5 Draft AO,²⁰ which gives costs for cold curation between -20°C and -80°C of \$35 million (\$15 million for room temperature). Because of Gelato's lean science payload, given that the majority of the science objectives would be satisfied through ground-based laboratory analysis, the science team could not identify any part of the payload that could be descoped. Therefore, the baseline and threshold mission requirements are identical.

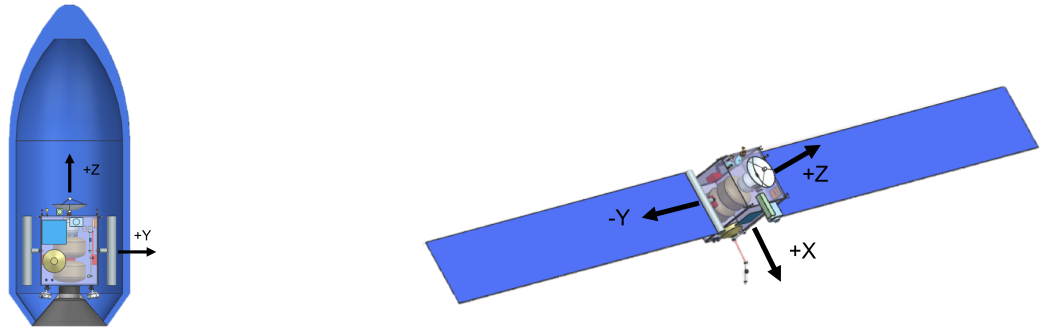
NF4 requires that proposed technologies exceed the appropriate technology readiness threshold or that appropriate time and resources are allocated for the necessary testing and development. These requirements as they apply to the spacecraft subsystems are discussed in the following subsections. At a system level, the vehicle achieves full compliance with the high-performance 5 m fairing Expendable Launch Vehicle from the NF4 AO library. The choice of this class of launch vehicle is derived from the required C3 of $68\text{ km}^2\text{ s}^{-2}$, leading to a maximum launch mass of 3145.8 kg. The vehicle has no nonstandard requirements. Due to the size of the fairing

required for the Gelato spacecraft design (Figure 9), the cost cap was reduced to \$988 million FY25, due to cost decrement for upgrading to a high-performance launch vehicle from the standard that NASA provides. Overall, the cost of the Gelato mission concept development, Phases A–D, was estimated at \$928.4 million FY25 and would therefore be achievable under the constraints of NF4.

5.2. Propulsion Subsystem

The Gelato spacecraft would utilize solar electric propulsion (SEP), like NASA's Evolutionary Xenon Thruster—Commercial (NEXT-C; R. Shastry et al. 2017), for all the proposed deep space travel, as well as trajectory correction maneuvers (Table 5). Additionally, a hydrazine (N_2H_4) monopropellant propulsion system, like the Aerojet MR-111C (V. Yarnot et al. 2016), would be used for proximity operations at the comet. The monopropellant propulsion system would be operated in a simple blow-down formation, with its 12 thrusters allowing for enough rotational and translational degrees of freedom to adequately perform the intended mission. Additional propellant would be allocated for the reaction control system (RCS)

²⁰ <https://newfrontiers.larc.nasa.gov/NF5/announcements.html>



(a) Gelato in its stowed, launch configuration inside a high performance 5 m ELV payload fairing.

(b) Gelato with ROSA deployed and BiBlade arm extended.

Figure 9. Different configurations of the Gelato spacecraft.

Table 5
Propulsion Subsystem Specifications

Event	System	Engine	Avg Thrust (N)	Avg I_{sp} (s)	Propellant Allocation (kg)
SEP cruise	SEP	NEXT-C	0.0784	3673.50	734.5
Statistical	SEP	NEXT-C	0.0784	3673.50	3.15
Rehearsal and operations	Monoprop	Aerojet MR-111C	4.45	229	98.8
RVS propellant allocation from ACS	Monoprop	Aerojet MR-111C	229	300	20

owing to requirements from the attitude control subsystem (ACS). Both subsystems may employ commercially available parts that satisfy the thrust and specific impulse (I_{sp}) requirements set by the large delta-V of the proposed comet encounter and mission.

5.3. Power Subsystem

Due to the spacecraft's aphelion of under 6 au, usage of an appropriately sized solar array would provide sufficient power to meet mission objectives, thereby avoiding usage of a plutonium oxide heat source in radioisotope thermoelectric generators (Table 6). Since the sampling location would be at the base of an outcropping, the solar array would be retracted to minimize risk of damage to the arrays and spacecraft during the descent and sampling maneuver. Two wings of Roll-Out Solar Arrays (ROSA) were selected and are a key driver of technological development. The deployment and retraction of these arrays were tested on the International Space Station (J. Banik et al. 2018; B. R. Spence et al. 2018) and successfully employed on the Double Asteroid Redirection Test (DART) spacecraft (J. Bellerose et al. 2024). The lunar Gateway mission will also employ similar solar arrays (M. Aulisio et al. 2020). Power storage on Gelato would be accomplished through lithium-ion batteries.

5.4. Thermal Subsystem

Based on thermal design specifications, the avionics and telecommunications for Gelato would be required to remain between -20°C and 50°C ; the batteries, between -10°C and 20°C ; and the xenon tanks and lines, between 25°C and 45°C . This would drive most of the spacecraft to be bounded between 25°C and 45°C , except for the batteries, which would

have their own dedicated radiator. The radiator size and heater power requirements were calculated according to a cold bias design, where radiator size is selected based on the hottest portion of the mission and the heater power requirements are determined based on the coldest portion of the mission. Gelato would experience its hottest thermal loading during the SEP cruise near Earth. Based on this case, a radiator area of 1.54 m^2 would be sufficient. This radiator size in the coldest scenario of eclipse at the comet would lead to high heater power needs. In order to reduce those needs, louvres would be added over the radiators to reclaim heat, leading to a maximum heater power of 95.5 W .

5.5. Attitude Control Subsystem

The ACS was designed to meet the pointing requirements with margin and redundancy (Table 7). It was selected based on OSIRIS-REx flight heritage and does not require any significant new developments (E. Bierhaus et al. 2018). The attitude determination system would consist of two star trackers, two inertial measurement units, and six two-axis coarse Sun sensors. The control system would include four reaction wheels and the RCS thrusters in the propulsion system. The spacecraft would be able to enter several operational pointing modes as required by the mission, including nadir-pointing, Sun-pointing, inertial, and safe modes. Note that all modes would ensure that the sensor deck and specifically the pushbroom camera, hyperspectral imager, and sampling and descent cameras are pointed away from the Sun. Nadir-pointing mode would be utilized for observations and data collection and thus would require that the sensor deck be pointed such that 67P be within the fields of view of the instruments. Sun-pointing mode would orient the vehicle and

Table 6
Power Subsystem Specifications

ROSA Specifications	Value
Power generation/requirement ^a	35 kW (beginning of life); 1.8 kW (end of life)
Size	115 m ² (mechanical); 99 m ² (effective)
Axis of rotation	Single axis gimbaled
Solar cell type	Triple junction
Efficiency	29.5%
Lithium-ion Battery Specifications	
Storage capacity ^b	324 Ah
Worst-case depth of discharge	47%
High-voltage Electronic Assembly Specifications	
Electric propulsion	80–150 V
Other	28–32 V

Notes.

^a Driven by electric propulsion (5% growth factor on EP, 43% on other systems).

^b Driven by 6 hr sample collection mode.

Table 7
Spacecraft Attitude Control System Pointing Requirements

Requirement	Value
Pointing Knowledge (1σ)	6"
Pointing control (1σ)	30"
Stability	8.5 s ⁻¹
Slew rate	≤0.1 s ⁻¹
Translation maneuver control	4 cm s ⁻¹ ± 3 cm s ⁻¹

solar arrays toward the Sun for power generation purposes. Inertial pointing mode could be leveraged for a variety of other tasks, including telecommunications or calibration events. Finally, the safe modes would be leveraged in the case of an anomaly to point the vehicle to maintain sufficient power generation and communications with Earth. While some activities, such as sample collection, would operate under battery power, most modes would point the vehicle or gimbal the solar arrays such that the system remains power-positive.

5.6. Command and Data-handling Subsystem

The conceptual command and data-handling subsystem (CDS) architecture can be seen in Figure 10. Housekeeping data generation would be under 1×10^{-3} Mbits s⁻¹. The data storage unit selected has a storage size of 8×10^3 Mbits. While the industry contractor hired to build the CDS may not choose the space-qualified LEON 3 processor in Sphinx, it would be representative of the current generation of low-power (non-RAD750) processor architectures that are in use throughout the space industry and have been prevalent over the past decade

(T. Imken et al. 2017; P. Bambach et al. 2018; P. C. Lai et al. 2020).

5.7. Telecommunications Subsystem

All communication with the spacecraft would occur over X band using a dual-string telecommunications subsystem. The system would consist of a 1.5 m parabolic dish high-gain antenna (HGA), a medium-gain conical horn antenna (MGA), and two choked horn low-gain antennas (LGAs). The LGAs provide support for launch and initial maneuvering near Earth. In addition to providing communications capability at intermediate distances, the MGA would be placed on the zenith side of the spacecraft and would send ranging tones to establish spacecraft status and health during rehearsals and sampling. During data collection in the HAMO and LAMO phases (Section 4.3), 10% and 20%, respectively, of the sampling time would be reserved for HGA data downlink, while 100% of the night-time orbit could be used for telecommunications. The HGA would be sized to provide an uplink and downlink (UL/DL) 8.8 kps science data rate at more than 6 au, with safe mode rates 7.825 bps (UL) and 10 bps (DL). The science data rate would be sufficient to return all needed data and would only improve as the spacecraft follows the comet toward perihelion. All antennas would be powered by a redundant 65 W traveling wave tube amplifier (TWTA) system, and the X-band radio signal is generated by the Universal Space Transponder (UST; M. Pugh et al. 2017). We would choose X band over Ka band to reduce the system size and leverage previously flown components for reliability and nonrecurring engineering cost savings. The LGAs and MGA (J. D. Vacchione et al. 2012), as well as the TWTA (S. W. Asmar et al. 2017), would be based on those flown on Juno. The UST radio would be the same as used for NASA–India Space Research Organization Synthetic Aperture Radar (M. Pugh et al. 2018).

5.8. Ground Operations

Gelato would use the Advanced Multi-Mission Operations Systems and standard JPL processes adapted to mission-specific needs for command uplink and data downlink between mission control and the spacecraft (A. Ko et al. 2010). Staffing for ground operations would follow standard JPL procedures and policies for training and staffing during each mission phase. Data would be downlinked from the spacecraft to the Deep Space Network using the X band at a rate of 8.8 kbps at 5.57 au, and that rate would increase closer to Earth. The data downlink capabilities of the spacecraft would be approximately 250 Mb day⁻¹, with an expected data volume of 192 Mb day⁻¹, allowing for a 58 Mb day⁻¹ (~23%) downlink margin. Downlinked data would be sent to the mission control and science data processing center and then archived at a data archiving facility (e.g., Planetary Data System) and/or the data analysis facility of the mission (e.g., PI institution). Earth-to-spacecraft uplink frequency would vary depending on the mission stage (Table 8). During the cruise stage, commands would be uplinked monthly; during the HAMO phase, commands would be uplinked on a 2-week cycle, and during LAMO and sample collection, commands would be uplinked weekly. The data uplink rate would be 2.0 kbps.

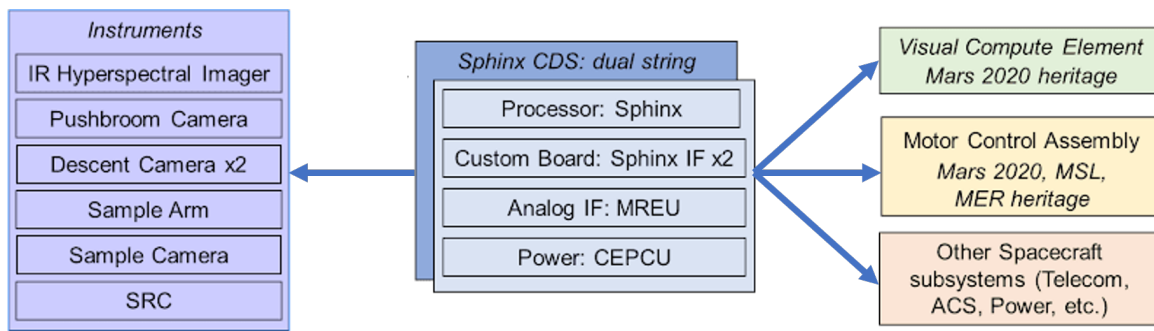


Figure 10. The CDS architecture for the Gelato spacecraft. Analog intermediate frequencies would be handled by the Multi-Mission System Architecture Platform Remote Engineering Unit (MREU), while power commanding would be controlled by a Compute Element Power Conditioning Unit (CEPCU).

Table 8
Uplink and Downlink Command Frequency

Mission Phase	Uplink Frequency
Cruise	Monthly
HAMO	2 week Cycle
LAMO and sample collection	Weekly
Spacecraft-to-Earth Downlink Frequency	
Launch +1 month	Continuous
Cruise	Weekly
67P encounter + 1 month before and after	Daily
Sample rehearsals and capture	Continuous
2 months prior to Earth return	Daily
Last several weeks prior to return	Continuous

Spacecraft-to-Earth downlink frequency for each mission phase is described in Table 8.

5.9. Mechanical Structure and Configuration

The main spacecraft would be a four-sided bus with dimensions $2.5 \text{ m} \times 2.5 \text{ m} \times 3 \text{ m}$ and a predicted dry mass of 1686.8 kg, incorporating a 22% margin. The overall geometry of the bus design was primarily dictated by the 5.2 m fairing of the proposed launch vehicle (Figures 9 and 11). The fairing envelope would have to accommodate the spacecraft bus and two laterally mounted ROSA wings, which are rolled back during launch. Science instruments would be mounted on the nadir facing (+X) instrument deck. The 1.5 m parabolic HGA would be mounted atop the bus on the +Z face, and the two articulated ROSA wings would be mounted on the +Y and -Y faces. Given the strict pointing and attitude requirements, the spacecraft would be three-axis stabilized by means of a complementary system of reaction wheels and thrusters. The pyramidal configuration of reaction wheels would be expected to provide both robustness and redundancy. The primary NEXT-C engines would be mounted on the -Z face of the spacecraft and would be gimbaled, enabling both SEP cruise and statistical maneuvers.

The primary structure would be made from aluminum honeycomb with graphite composite face sheets. The selected materials would provide a lightweight structure with sufficient strength to support other spacecraft elements, survive launch

loads, and provide high stiffness for pointing/control requirements. The spacecraft core cylinder would provide an axial load path during launch and also contain the propellant tanks ($2 \times \text{SEP}$ and one monopropellant).

5.10. Development

The primary areas of development for Gelato would include scaling ROSA for the Gelato use case and software development necessary for integrating the operational needs of disparate components of the spacecraft. DART successfully demonstrated the use of ROSA for its power source, providing precedent for the use of ROSA for small-body missions (J. Bellerose et al. 2024). Furthermore, the Gateway in the Artemis program will also employ significantly larger ROSA panels to power the station (M. Aulisio et al. 2020). However, the driver for technical development is Gelato's distance from the Sun compared to the DART spacecraft. DART remained in an orbit similar to Earth's orbital radius around the Sun. By contrast, Gelato would reach a maximum heliocentric distance of 5.77 au, and the sampling maneuver would occur between 5.57 and 2.6 au. Whereas DART's panels were functional for ~ 10 months, Gelato would have a nominal operational life span of a little under 13 yr. The Gateway ROSA panels are also rated for 15 yr (M. Aulisio et al. 2020). As such, the technological development required would ensure maturity of the panels for the extended life span at the required distance from the Sun, as well as for the retraction and deployment during the sampling maneuver in these conditions.

Software development is another key area of development that would be required during mission design. The unique combination of heritage and novel components implemented on the spacecraft would require significant investments in integrating spacecraft subsystems. The Navigation, Sample Acquisition, and Hazard Avoidance software for the descent stage, which employs visual processing for navigation, would likely be the most complicated part of this development. Medium software heritage exists for most other aspects of Gelato, so the code likely could not be directly reused without modifications.

6. Conclusion

The study presented here outlines a mission concept studied by the 2022 JPL PSSS to acquire and return a nucleus sample from comet 67P/Churyumov-Gerasimenko. The Gelato mission concept would have a lean architecture, with a high heritage scientific payload and a focus on collecting and returning a single nucleus sample. Returning a comet nucleus

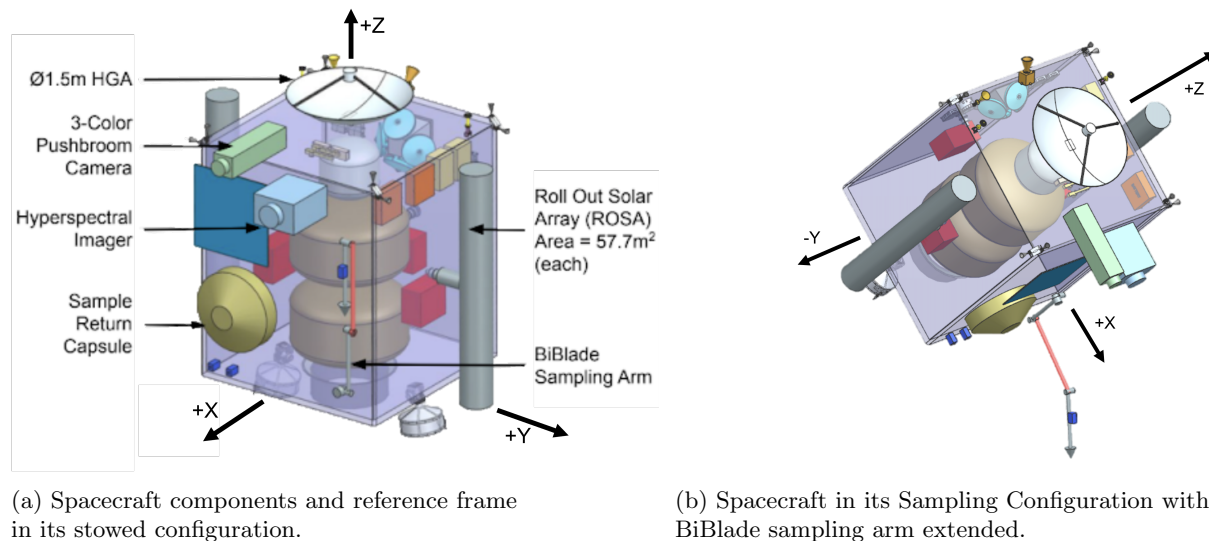


Figure 11. The mechanical structure and configuration of Gelato, with all components discussed in Section 5 visible.

sample to Earth for analysis would provide critical information, leading to a deeper understanding of the early solar system and the presolar processes that led to its formation. A CSSR mission would not only further our understanding of solar system origins but also tap into a deeper human desire to unravel the mysteries of the origins of life and our place in the Universe.

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Appendix A Hyperspectral Imager Observables

We would determine the spectral properties of the comet surface to select the most suitable sample to achieve science closure for all objectives. Below we describe relevant minerals for each objective and their relevant spectral properties.

For Objective 1, we would identify any spectral signatures that are consistent with plagioclase feldspar ($\text{NaAlSi}_3\text{O}_8$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$), an Al-bearing mineral that may be present in the

refractory material on the cometary nucleus surface (O. J. Stenzel et al. 2017). A steep negative slope from 4.0 to 4.5 μm ($-30\% \pm 10\%$ reflectance) is indicative of plagioclase (Figure 5). This slope is due to stretching and bending vibrations of Si–O and Al–O bonds (D. B. Nash & J. W. Salisbury 1991) and a possible reflectance band minimum centered at 1.1–1.3 μm (due to small amounts of Fe^{2+} electronic transitions J. B. Adams & L. Goullaud 1978). Confounding materials for plagioclase in this wavelength range are Fe-bearing minerals that have strong spectral features near 1 μm that will often overpower the 1.1–1.3 μm band observed in plagioclase (Figure 5). Olivine has a single broad, deep, asymmetrical band centered between 0.9 and 1.3 μm (e.g., J. B. Adams 1968); pyroxene has two absorption bands centered at 0.9–1.05 μm and 1.9–2.2 μm (e.g., J. B. Adams 1968); basaltic glass has one shallow, broad absorption at 1.07–1.20 μm and sometimes a shallow, broad absorption centered near 2 μm (e.g., J. B. Adams 1974; M. E. Minitti et al. 2002; B. H. Horgan et al. 2014). Plagioclase is relatively transparent and must be present in large amounts ($>60\%$) to be spectrally detectable near 1 μm (E. A. Cloutis & M. J. Gaffey 1991). A spectral resolution of <25 nm with a <33 GSD is required to confidently determine the presence of plagioclase.

We would search for surface exposures of H_2O and CO_2 ices (Figure 5) for Objective 2. Spectral features of H_2O ice include a narrow, shallow, asymmetrical absorption centered at 1.26 μm and a broad, deep, asymmetrical absorption centered at 1.5 μm due to an O–H overtone stretch; a broad, deep, and symmetrical absorption centered at 2.02 μm due to H–O–H bend and O–H stretch combination; and an overall negative slope from ~ 1 μm into longer wavelengths (R. N. Clark et al. 2013). Spectral features of CO_2 ice include narrow and sharp absorption bands centered at 1.43, 1.58, 1.93, 1.97, and 2.03 μm (all due to different vibrational modes; P. Gerakines et al. 2005, and references therein); a broad, asymmetrical band from 1.85 to 2.15 μm that encompasses a complex of the previously mentioned sharp, narrow bands; a broad, deep, slightly asymmetrical band from ~ 2.6 to 3.3 μm due to CO_2 combination bands; a deep, narrow, slightly asymmetrical band at 4.19 μm due to a C=O stretch; and a shallow, narrow, symmetrical band at 4.31 μm due to CO_2 stretching

(K. Isokoski et al. 2013). A confounding material to differentiate from is CH_4 (methane) ice, which has a similar diagnostic absorption band near $3\text{ }\mu\text{m}$ to CO_2 (e.g., W. Grundy et al. 2002). A spectral resolution of $<5\text{ nm}$ with a $<33\text{ GSD}$ is required to resolve differences between H_2O , CO_2 , and CH_4 ice.

Organics present to address Objective 3 may include aromatics, aliphatics, alkenes, alkynes, alcohols, amines, amides, nitriles, carboxylic acids, ketones, and/or aldehydes (e.g., S. A. Sandford et al. 2006; H. Yabuta et al. 2018; G. Filacchione et al. 2019; A. Raponi et al. 2020). In general, organics can have absorption bands due to C–H bonds centered at $0.75\text{--}0.82\text{ }\mu\text{m}$, $2.7\text{--}3.0\text{ }\mu\text{m}$, and $3.36\text{--}3.52\text{ }\mu\text{m}$; C–C bonds centered at 1.6 and $2.2\text{ }\mu\text{m}$; C–O bonds at $1.1\text{ }\mu\text{m}$ and $1.64\text{--}1.73\text{ }\mu\text{m}$; N–H bonds centered at $3.2\text{--}3.3\text{ }\mu\text{m}$; and O–H bonds centered at 3.1 and $3.35\text{ }\mu\text{m}$ (e.g., R. N. Clark et al. 2009). Figure 5 highlights four organic groups that we can search for and the specific spectral features used for identification. For the purposes of the mission, and based on what we observe in laboratory spectra in Figure 5, identifying at least two of the following features would allow for confident organics ID: a narrow, shallow, symmetrical absorption centered at $0.9\text{ }\mu\text{m}$; a narrow, shallow, symmetrical band complex from 3.2 to $3.4\text{ }\mu\text{m}$; and a broad, deep, triplet absorption from 3.4 to $3.6\text{ }\mu\text{m}$. The spectral characteristics of organics have many similarities to those of carbonates (fundamental absorption bands centered at ~ 3.5 and $\sim 4.0\text{ }\mu\text{m}$; J. W. Salisbury et al. 1987; J. Bishop et al. 2021) and clay minerals (diagnostic absorption bands centered at $0.89\text{--}0.93\text{ }\mu\text{m}$, $1.4\text{ }\mu\text{m}$, $1.9\text{ }\mu\text{m}$, and $2.1\text{--}2.5\text{ }\mu\text{m}$ dependent on composition; J. L. Bishop et al. 1994; J. Bishop et al. 2008). To resolve differences between organics, carbonates, and clay minerals, a spectral resolution of $<5\text{ nm}$ with a $<33\text{ m GSD}$ is required.

Appendix B Comet Selection

Our mission was initially designed to be target-agnostic: we developed our science objectives and many of the requirements for instruments and sampling before we selected our target comet. This was done to ensure that, when designing objectives, the mission would be informed by the larger population of JFCs rather than the specific attributes of a target comet.

After the science objectives were sufficiently delineated, trajectory planning was conducted to determine a target comet. The criteria used for comet selection included an aphelion distance $\leq 6\text{ au}$, an inclination $\leq 7.05^\circ$, a perihelion distance of $1 \pm 0.5\text{ au}$, and >1000 ground-based observations. These orbit and observation parameters were defined to limit the length of our spacecraft trajectory and cruise duration while selecting for comets with well-known orbits.

Our trajectories were further constrained by our launch window, our science and sampling requirements, and our directive to return a sample from the comet’s surface to Earth. Our science and sampling needs required a period of reconnaissance of the comet’s surface and that sampling be conducted at distances of $>2.5\text{ au}$, following the recommendations from N. Attree et al. (2019) and C. Lisse et al. (2022). At distances closer than 2.5 au , forces due to cometary outgassing dominate over cometary gravity forces, which can cause difficulties for conducting proximity operations. In addition, because perihelion can bring about significant thermal changes and outgassing, the reconnaissance phase cannot be separated from the sampling phase by a perihelion. Therefore, the reconnaissance phase must occur after the comet has ceased to be active post-perihelion, and sampling must occur before the next perihelion. Trajectories used to determine potential candidates were based on the preliminary spacecraft design and were used to provide a comparison between targets.

The comets that were identified with the above criteria were 67P/Churyumov–Gerasimenko, 88P/Howell, 45P/Honda–Mrkos–Pajdusakova, 15P/Finlay, 304P/Ory, and 104P/Kowal 2. Comets 67P and 88P emerged as ideal candidates. Comet 67P was selected as the primary target, due to both the extent of previous characterization (Section 4) and the low delta-V requirements and spacecraft trajectories for the expected launch window. The final trajectory for 67P was modified to account for changes in the spacecraft design during Point Design with Team X.

Comet 88P was identified as a secondary target with an expected spacecraft trajectory of similar duration and delta-V requirements with a $\sim 8\text{-month}$ launch delay. According to preliminary trajectory studies, switching from 67P to 88P would not require substantial changes to the mission architecture or amount of propellant. If Gelato was unable to meet the launch window for 67P, there would then be an 8-month window to prepare for a launch to 88P.

Studies of comet 88P suggest that it contains the necessary material for science closure on all objectives. Remote compositional studies have demonstrated that its isotopic abundances are representative of JFCs for C and N based on measurements of CN and HCN (D. Hutsemékers et al. 2005). It is rich in CO_2 (W. T. Reach et al. 2013), which suggests likely trapping of substantial hypervolatiles and fulfillment of Objective 2 (Section 2.3). Like 67P, it may have surface variation with an isolated dominant water source migrating from winter to summer hemispheres (D. Schleicher et al. 2020).

Appendix C Science Traceability Matrix

Figure 12 displays the full Science Traceability Matrix for the Gelato mission.

	Science Objectives	Science Measurement Requirements		Instrument Requirements	Projected Performance	Mission Requirements
		Physical Parameters	Observables			
What role did nearby supernova trigger the molecular cloud's collapse into pre-solar disk?	Objective #1: Determine whether early compositional reservoirs of short-lived radionuclides in the protoplanetary disk were (1) homogeneous or (2) heterogeneous between the inner solar system CAI and Chondrule forming regions and the outer solar system comet's formation region.	1.1 26Mg/24Mg, 26Mg/25Mg, 27Al/24Mg, 26Al/27Al (2σ < 8 ppm) for age (2σ < 1 My) and initial abundance	Miz: 24Mg (23.985), 25Mg (24.9858), 26Mg (25.9826), 27Al (26.9815) and CS [23] 48Ca2+ (23.975). Mass needed determined by Pb.	Detectability threshold: <1E6 molecules Mg/Al, range: 23-275 m/z, RP [22] > 2696.15 at m/z 26.9 Mn/Cr, range: 48.5-16 m/z, RP [22] > 2115 at 55 m/z	Range: (m/z - m/z x 2), RP [22]: 10,000 at m/z 58, Spatial Res.: 50 nm	Sample Handling Requirements: No. of samples: 1 Sample State: solid Sample Mass: ≥3.2 g (800 mg + 75% storage allocation) Temperature: <60°C SRC Requirements: Hermetic seal; Temperature control at <25°C; Separate volatiles containment
	(1) 26Al assumed homogeneous between CAI and comet formation region (4-sigma difference in 26Al from canonical model).	1.2 52Cr/50Cr, 53Cr/52Cr, 54Cr/52Cr, 55Mn/52Cr, 53Mn/55Mn for age comparison to Al-Mg and to date alteration (2σ < 14 ppm, < 1 My)	Miz: 50Cr (49.9460 m/z), 52Cr (51.9405 m/z), 53Cr (52.9408 m/z), 54Cr (53.9398 m/z), 55Mn (54.9380 m/z) and CS [23] 40Ar/41Ar (53.9654 m/z) Mass needed determined by Pb.			
	(2) Supernova trigger predicts 26Al heterogeneous between CAI and comet formation region (4-sigma difference from canonical model).	1.3 206Pb/204Pb, 207Pb/209Pb, 207Pb/235U, 206Pb/238U (2σ < 1 ppb) for absolute age (2σ < 1 ppb)	Miz: 204Pb (203.9730 m/z), 206Pb (205.9745 m/z), 207Pb (206.9759 m/z), 209Pb (208.9809 m/z), 235U (235.0439 m/z) and CS [23] 204Hg (203.9735 m/z) Mass: Pb is rarest and determines mass needed (80 mg samples x 10 = 800 mg)	Detectability threshold: <1E6 molecules Range: 202-240 m/z RP [22] > 238 at m/z 238		
What role did comets play in the delivery of volatiles to Earth's atmosphere and interior?	Objective #2: Determine whether volatiles were predominantly delivered to Earth via an early bombardment of 67P-like comets. [1]	2.1 Abundance of stable isotopes of H (for 8D ±10%, [21]) in H2O	Miz: H2O (18.011 m/z), DHO (19.021 m/z), D2O (20.023 m/z) and CS [23] 18O (17.999 m/z), DO (18.009 m/z), 15NH3 (18.024 m/z), N4H (18.034 m/z), 16OH (19.007 m/z), H2-17O (19.015 m/z), H3O (19.018 m/z), 7O (19.011 m/z), 19F (18.998 m/z), Ne (19.992 m/z), HF (20.007 m/z), H2-18O (20.015 m/z), THO (20.019 m/z), H2DO (20.028 m/z) with res. <0.02 m/z. Mass: 2.72E-06 mg x 10	Detectability threshold: >1E4 molecules H2O, range: 17-21 m/z, RP [22] > 36 at 18 m/z NH3, range: 16-19 m/z, RP [22] > 36 at 18 m/z H2O, range: 27-30 m/z, RP [22] > 56 at 28 m/z	Range: 17-30 m/z RP [22]: 200 for N isotopes and > 1000 for H isotopes Available molecules per sample test: 1E8	Sample Handling Requirements: No. of samples: 1 Sample Mass: >172.4 mg (118.1 mg + 75% storage allocation) Sample location: Minimum areal deposition sites (e.g. central Inhofen on 67P) Temperature: <60°C Contamination control: Dry N2 used in labs must be well-characterized (isotopic ratios and abundances) SRC Requirements: Hermetic seal; Temperature control at <25°C; Separate volatiles containment
	(1) JFCs played a predominant role in delivering volatiles: 8D and 8N = Earth ocean and atm (8D = 8N = 0 within 3σ); Xe, Kr, and Ar = Earth atm; and 67P coma ≠ surface	2.2 Abundance of stable isotopes of N (for 8N ±10%, [21]) in NH3 and N2	Miz: N2 (28.006 m/z), 15NN (29.0032 m/z) and CS [23] CO (27.956 m/z), DCO (28.017 m/z), CH2N (28.038 m/z), C2D2 (28.046 m/z), 13CO (28.988 m/z), H2O (29.0027 m/z), N2H (29.014 m/z), CH3N (29.04 m/z) and C2H5 (29.06 m/z) with res. < 0.008 m/z. NH3 (17.027 m/z), 15NH3 (18.024 m/z) and CS [23] OH (17.003 m/z), 13CH4 (17.034 m/z), CH5+ (17.039 m/z), 18O (17.999 m/z), H2O (18.011 m/z), DO (18.009 m/z), and NH4 (18.034 m/z) with res. <0.01 m/z. Mass: 1.66E-03 mg x 10 for NH3; 9.30E-08 mg x 10 for N2 in refractories			
	(2) JFCs played a minor role in delivering volatiles: 8D and 8N ≠ Earth (8D ≠ 8N ≠ 0 within 3σ); Xe and Kr = 67P coma; Ar = chondritic; and 67P coma = surface	2.3 136Xe/132Xe and 128Xe/132Xe ± 0.02	Miz: 128Xe (127.90 m/z), 132Xe (131.90 m/z), 136Xe (135.91 m/z) and CS [23] 146Xe (147.88 m/z), H2 (2.015 m/z), Mass: 136Xe is rarest and determines mass needed (11 mg samples x 10 = 110 mg)	Detectability threshold: <1E6 molecules Xe, range: 127-137 m/z, RP [22] > 13.600 at 136 m/z Xe, range: 51-67 m/z, RP [22] > 3.405 at 96 m/z Ar, range: 35-39 m/z, RP [22] > 3.800 at 36 m/z	Detectability threshold: 5E5 molecules Mass range: 35.39, 81-87, and 127-137 m/z Mass resolution: m/zm > 3000	Temperature control at <25°C; Separate volatiles containment
2022 DS priority questions Q3 - Origin of Earth & Inner SS Bodies, Q10 - Dynamic Habitability	Objective #3: Determine whether comet 67P is host to biologically relevant molecules (amino acids, N-heterocycles, hydroxy acids, sugars, fatty acids) and molecules with enantiomeric excess consistent with biology (L-amino acids, D-sugars), and if so, whether they formed in (1) presolar interstellar environments, (2) the protoplanetary disk, or (3) as a consequence of parent-body processes.	2.4 82Kr/84Kr and 86Kr/84Kr to ± 0.02	Miz: 82Kr (81.912 m/z), 84Kr (83.91 m/z), 86Kr (85.91 m/z) and CS [23] C6H10 (162.1436 m/z), C8H14 (168.1102 m/z) with res. <0.1 m/z. Mass: 82Kr is rarest and determines mass needed (7 mg samples x 10 = 70 mg)			
	(1) Organics formed via irradiation of ISM/solar ices: (A) affiliated with ice residues, presolar grains, and volatile elements; (B) anomalously heavy isotopic values; (C) prominent in 67P compared to primitive meteorites	2.5 36Ar/38Ar ± 0 ± 0.3	Miz: Relative abundance to ± 0.02 of 36Ar (35.96 m/z), 38Ar (37.96 m/z) and CS [23] H-35Cl (35.977 m/z), H2-34S (35.988 m/z), 36S (35.966 m/z), CS2+ (37.972 m/z), H-37Cl (37.977 m/z), C2H (38.003 m/z) and C2H2 (38.016 m/z) with res. <0.01 m/z. Mass: 38Ar is rarest and determines mass needed (5.0 mg samples x 10 = 5 μg)			
	(2) Organics formed via gas-phase chemistry in the inner solar nebula: (A) affiliated with metals that catalyze reactions; (B) depleted C, H, N, O isotopic values; (C) prominent in 67P compared to primitive meteorites	3.1 Amino acids (to <1 ppm), hydroxy acids (to <1 ppm), N-heterocycles (to <10 ppm), sugar derivatives (to <10 ppm), fatty acids (to <1 ppm)	Miz [12]: Amino acids (76.0393 - 205.09715 m/z), hydroxy acids (72.95311 - 187.996245 m/z), N-heterocycles (112.05054 - 152.05668 m/z), sugars/derivatives (LCMS: 91.03896 - 151.07083 m/z), sugar derivatives (GCMS: 171.05 - 387.12 m/z), fatty acids (73.0255 - 338.32685 m/z). Mass: 0.15g x 10 each for N-heterocycles and sugars; 0.01g x 10 each for amino acidity/chirality and fatty acids	LC-MS Range: 72-467 m/z, Accuracy: <5 ppm, RP [22]: 46,700 at 467 m/z	Range: 50-6000 m/z, Accuracy: <1 ppm, RP [22]: 140,000 at 555.62 m/z	Sample Handling Requirements: No. of samples: 1 Sample State: solid Sample Mass: >25.2 g (6.3 g + 75% storage allocation) Sample location: Location where organics have been detected using IR; presence of days are minimal Sampling depth: >100 nm Temperature: <25°C long term storage @ <80°C Contamination control: 100 particulate requirement, nonvolatile residue level A2 (500 ng/cm2), <180 ng/cm2 of amino acids on sampler head, 2 witness plates SRC Requirements: Hermetic seal; Temperature control at <25°C; Separate volatiles containment
Did comets deliver biologically-relevant organics to Earth, and if so, what were the origins of these cometary molecules?	(1) Organics formed via irradiation of ISM/solar ices: (A) affiliated with ice residues, presolar grains, and volatile elements; (B) anomalously heavy isotopic values; (C) prominent in 67P compared to primitive meteorites	3.2 Compound-specific isotope ratios (δD, δ13C, δ15N, δ18O) in biologically-relevant soluble organic matter (SOM) and insoluble organic matter (IOM) (OM: 8D: ±100 ‰, 8N: ±100 ‰, 8C: ±50 ‰, 8O: ±20 ‰, SOM: 8D: ±10 ‰, 8N: ±2 ‰, 8C: ±1 ‰)	m/z [LCMS]: DvH: (1.006277 Da + m/z) vs m/z; 15Nv14N: (8.017030 Da + m/z) vs m/z; 18O vs 17Ov16O: (2.004244 Da + m/z) vs (1.004216 Da + m/z) vs m/z; [IRMS] 12CO2 (43.989); 13CO2 (44.993); H2 (2.015); HD (3.022); D2 (4.028); Mass: 0.15g/10 = 1.5g amino acid/analyte; 6 g of residue from soluble organic analysis (3.1 ±2.34)	GC-MS Range: 72-467 m/z, Accuracy: <5 ppm, RP [22]: 46,700 at 467 m/z	Range: 50-6000 m/z, Accuracy: <1 ppm, RP [22]: 140,000 at 555.62 m/z	
	(2) Organics formed via gas-phase chemistry in the inner solar nebula: (A) affiliated with metals that catalyze reactions; (B) depleted C, H, N, O isotopic values; (C) prominent in 67P compared to primitive meteorites	3.3 Coordinated analysis of organic molecules (spatial resolution < 100 nm) with a Pearson correlation to statistically relate the association of organic molecules with presolar grains, ices, volatiles, metals, and minerals	Organics: see PP 3.1 LIBS: H (656.21 nm), C (247.88 nm), O (777.35 nm), S (469.50 nm), P (213.62 nm), Cl (837.57 nm), Na (589.14 nm), Fe (248.70 nm), Cr (283.59 nm), Ni (224.67 nm) SEM-EDS: C (Kα 2.82), O (Kα 0.277), Si (Kα 1.739), N (Kα 0.393), Kr (Kα 5.411; Lu 0.573); Na (Kα 1.041); Ca (Kα 3.690) Minerals via Raman: magnetite [15], hematite [14], graphite [15], serpentine [15], calcite [17], dolomite [18], siderite [15], magnesite [20] Presolar grains via Nano-SIMS: 54Fe (53.9396 m/z), 56Fe (55.935 m/z), 57Fe (56.9354 m/z), 28Si (27.9769 m/z), 29Si (28.9765 m/z), 30Si (29.9738 m/z), H2O (20.023 m/z), 13C (13.0034 m/z) Mass: con-sized grains	GC-MS Range: 248-776.8 nm, Res.: <0.1 nm EDS Res.: 20 nm EDS Res.: FWHM: 122 at 5.5 eV, FWHM: 2.3 nm	Range: 200-900 nm, Res.: 0.05 nm	
	(3) Organics formed via cometary parent-body processes: (A) be spatially affiliated with minerals indicative of parent-body processing; (B) isotopes representative of source reservoir mixing; (C) less prominent in 67P compared to meteorites	3.4 Enantiomeric excess, % D - %L, for amino acids, hydroxy acids, & sugars/derivatives (0-100% ee)	Abundance ratios: D and L enantiomers (to <1%) resolved via retention times & abundances from m/z peak areas. For m/z, see 3.3 Mass: Extracted from 3.1.	LIBS Range: 220 - 850 nm cm-1, Spatial Res.: <5 cm-1 FWHM, Spatial Res.: 0.3 cm-1 (FWHM), Spatial Res.: 0.25 μm (lateral), <1 μm (axial)	Range: 50-6000 m/z, Accuracy: <1 ppm, RP [22]: 140,000 at 555.62 m/z	
	Reconnaissance Requirements	Instrument Requirements		Projected Performance	Mission Requirements	
Mission Recon	R1. Near-global (>90%) surface morphology (to <0.5 m scales) for sample site selection to avoid obstacles and target recently exposed material	Images of at < 0.5 m resolution to distinguish between different morphologic units on 67P (cliffs, talus deposits, pitted plains, bouldered plains, smooth plains, cauliflower plains) to narrow down sampling sites. Sampling recently exposed materials is required which are consistent with cliff and talus deposit morphologies.		GSD: <0.25 m, SNR >20	GSD = 0.225 m, SNR > 42	HAMO Polar Orbital Radius: 25 km for primary recon Nadir Pointing Pointing Stability: <20 arcsec/sec Data generated over 10 orbital periods
	R2. Near-global (>90%) distribution of exposed minerals with 5±10% abundance precision per <100 m2 to select sample site with: (O1) the mineral plagioclase for chronology, (O2) H2O and CO2 ice for volatiles work, and (O3) C-H bonds in organics	Mineralogy (O1): Negative (<30% ± 10% reflectance) slope from 4.0 μm to 4.5 μm. CS [23]: Olivine [1], pyroxene [2] and Fe-bearing glass [3] Water (O2): 2+ bands of 1.5 ± 0.1 (28%, band depth), 2.0 ± 0.1 (55% band depth). CS [23]: CH4 [4] and CO2 ices. CO2 (O2): 2+ bands of 2.6-3.3 μm broad (96% band depth), 4.19 μm (96% band depth), and 4.31 μm. CS [23]: CH4 [4] and H2O ices. Organics (O3): 2+ bands of 0.9 μm (minimum 5.5% band depth), 3.2-3.4 μm complex (minimum 27% band depth), and 3.4-3.6 μm triplet (minimum 44% band depth). CS [23]: carbonates [8] and clay minerals [9]. Other bands not required for ID are in the white paper.		Spectral Range: 0.8 - 4.5 μm Spectral Res.: <5 nm GSD: <3 m, SNR >180	Spectral Range: 0.4-5.0 μm Spectral Res.: <5 nm, SNR > 400	LAMO Polar Orbital Radius: 25 km for in-depth recon and hazard avoidance at potential landing sites Nadir Pointing Pointing Stability: <20 arcsec/sec Data generated over >1+ orbital periods
Footnotes and References: [1] 1.2a Olivine: Band at 0.9-1.3 μm (e.g., Horgan et al., 2014). [2] 1.2b Pyroxene: Bands at 0.9-1.05 μm and 1.9-2.2 μm (e.g., Horgan et al., 2014). Plagioclase relatively transparent in 0.3-2.6 μm range and must be abundant (tens of percent) to be detectable (Cloutis & Gaffey, 1991). [3] 1.2c Fe-bearing glass: Bands at 1.07-1.20 μm and (shallow/broad) 2 μm (e.g., Horgan et al., 2014). [4] 2.2a Methane ice: Bands at 3.2-3.3 μm, 3.5 μm, and 3.8 μm (Grundy et al., 2002) and 3.43 μm (symmetric v1; Clark et al., 2003). [5] Detection threshold of < 1000 Xe atoms (Crowther et al. 2008) and < 5E5 molecules (Reynolds 1956 and Hohenberg 1989) well-documented. [6] Detection threshold of < 1E8 Ar atoms demonstrated by Saxton (2015). [7] Detection threshold of < 1000 Kr atoms demonstrated by Strashov et al. (2011). [8] 3.2a Carbonates: Molecular H2O overtones and OH molecules at 1.4 μm, 1.9 μm, and 3.0 μm. C-O bonds at 1.96-2.17 μm, 2.15-2.36 μm, 2.31-2.35 μm, 2.51-2.56 μm, 2.79 μm, and 3.35 μm with varying 2.3 μm and 2.5 μm values due to changes in cation atomic mass (Mg-OH). Carbonates at 3.5 μm and 4.0 μm. [9] 3.2b Clay minerals: Molecular H2O overtones and OH molecules at 1.39-1.42 μm, and 1.9-1.96 μm. If mineral is Fe-bearing, bands at 0.44 μm, 0.70 μm, and 0.89 μm-0.93 μm. Al-OH content at 2.21-2.25 μm. Fe-Mg-OH at 2.33 μm and 2.51 μm. OH bands between 2.86 μm, 2.73 μm, 2.941 μm, and 3.105 μm. [10] 67P values from Marty et al. (2017) (Xe), Rubin et al. (2018) (Kr), and Balsiger et al. (2015) (Ar). Solar wind values from Meakin et al. (2014). Earth's atmospheric values from Oelma and Podosek 2002. Q (chondritic phase) for Xe and Kr and AVCC (average chondritic phase) for Ar values from Busemann et al. 2000. AVCC for Ar value from Stauffer 1961, and U-Xe (theoretical primitive) value from Papin et al. 1999. [11] 3.3, for complete list of masses please contact the authors. [12] Tables 2 and 3 of Krieger, et al. (2015). [13] Magnetite: At 313.4, 471.8, 588.4, and 673.8 cm-1. [14] Hematite: At 284.2, 411.0, 500.1, 612.6, 662.7, 818.8, and 1041.7 cm-1. [15] Graphite: At 1360 and 1560-1580 cm-1. [16] Serpentine: At 230±10, 390±10, 690±10, and 3660-3700 cm-1. [17] Calcite: At 282.8, 718.2, and 1085.9 cm-1. [18] Dolomite: At 301.9, 725.5, and 1098.34 cm-1. [19] Siderite: At 301.9, 736.5, and 1089.5 cm-1. [20] Magnesite: At 330.7, 738.3, and 1094.8 cm-1. [21] δ(isotope) = [(isotope/reference)/Sample (isotope/reference)/Earth - 1] x 1000. [22] Resolving power (FWHM). [23] Confounding species.						

Figure 12. The STM that summarizes the Gelato mission goals and science objectives, along with the corresponding measurement, instrument, mission, and reconnaissance requirements. The abbreviated STM is included in Section 2.1.

ORCID iDs

Mallory J. Kinczyk  <https://orcid.org/0000-0002-7673-4479>
 Gabriel E. Buffo  <https://orcid.org/0000-0001-8709-5505>
 L. Miché Aaron-Hennig  <https://orcid.org/0009-0004-8863-184X>
 Spencer Boone  <https://orcid.org/0009-0003-5157-2148>
 Eric Frizzell  <https://orcid.org/0000-0003-4523-3951>
 Abigail Flom  <https://orcid.org/0000-0002-2897-5331>
 Chinmayee Govinda Raj  <https://orcid.org/0000-0003-4465-1692>
 Camilla Harris  <https://orcid.org/0000-0001-5045-8827>
 Ali Hyder  <https://orcid.org/0000-0002-3350-4243>
 Benjamin Idini  <https://orcid.org/0000-0002-2697-3893>
 Spiridon Kasapis  <https://orcid.org/0000-0002-0972-8642>
 Brennan McCann  <https://orcid.org/0000-0002-1722-5447>
 Emily Millman  <https://orcid.org/0009-0002-5075-943X>
 Alvin Ngo  <https://orcid.org/0000-0001-6114-6239>
 Mary Ringwood  <https://orcid.org/0000-0001-6916-1791>
 Laura E. Rodriguez  <https://orcid.org/0000-0002-2876-5051>
 Amanda Rudolph  <https://orcid.org/0000-0003-2911-9032>

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