Comet Interceptor: An ESA mission to a Dynamically New Solar System Object

J.P. Sánchez[a]*, G.H. Jones[b], C. Snodgrass[b] for the Comet Interceptor Science Team

[a] *Space Research Group, Centre of Autonomous and Cyber-Physical Systems, Cranfield University, UK*
[c]*Mullard Space Science Laboratory, Centre for Planetary Sciences, UCL/Birkbeck, UK.*
[d]*School of Physics & Astronomy, University of Edinburgh, UK.*
* Corresponding Author: jp.sanchez@cranfield.ac.uk.

Abstract

While the scientific merits of past comet missions are unquestioned, previously visited comets had all approached the Sun on many occasions and, as a consequence, have also undergone substantial compositional and morphological alterations. Comet Interceptor (Comet-I) was recently selected as ESA's first fast-track class mission and aims to explore a pristine comet, which will ideally be visiting the inner Solar System for the first time. Comet-I will hitch a ride to a Sun-Earth L2 quasi-halo orbit, as a co-passenger in ESA's M4 ARIEL's launch, in 2028. It will then remain there waiting for the right departure conditions to definitively leave the L2 point and intercept a newly discovered comet. Comet-I will be the first mission to be design and, possibly launched, without an identified target. Nevertheless, a Monte Carlo analysis modelling the uncertainties of the long period comet population and the spacecraft transfer capabilities demonstrate the high likelihood of completing the mission within 6 years. A few days before the closest approach Comet-I will release two small independent probes (~30 kg each) into fly-by paths with close approach distances in the order of a few hundred kilometres, while the main spacecraft (~700 kg) will take a safer path (~1000 km) to protect it from the dust environment. Comet-I will thus involve three spacecraft elements working together to ensure a low-risk, bountiful, interdisciplinary scientific return through unprecedented multipoint measurements.

Keywords: ESA, F-Class Mission, Comet Interceptor, Mission Analysis, Long Period Comets.

1. Introduction

The European Space Agency (ESA) selected in 2019 the Comet Interceptor (Comet-I) as its first Fast-track class mission (F-class). This newly created F-Class mission category enables mission opportunities that exploit joint launch opportunities with other ESA missions, and emphasizes implementation of novel space concepts. Comet-I will be launched in 2028 as a co-passenger with ESA's M4 ARIEL Mission on board an Ariane 6.2. It will be deployed in a Sun-Earth L2 quasi-halo orbit and remain there by means of small orbit maintenance manoeuvres for a period of up to 3 years; while it awaits for the right departure conditions to intercept a yet-to-be-discovered long period comet, which ideally would be visiting the inner Solar System for the first time.

Comets are highly valuable scientific targets to understand the formation and evolution of our Solar System. Previously visited comets, however, had approached the Sun on many occasions and, consequently, had undergone substantial surface compositional and morphological alterations. Comet-I instead aims at exploring a pristine newly discovered long period comet. By definition, Comet-I's target remains undiscovered, most likely beyond the orbit of Uranus in an in-bound trajectory towards the inner Solar System. Comet-I will rely on current astrometric survey efforts such as the soon-to-be-online Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), which will be conducting the most sensitive search ever performed. It is expected that Comet-I's target will be discovered when still beyond the orbit of Saturn, allowing for 3 years or more of warning time for Comet-I to fly to a feasible intersection point in order to briefly meet its target.

After the F-Class call selection, Comet-I successfully completed the internal CDF studies of the Assessment Phase (phase 0) [1], late in 2019. In February 2020, ESA approved advancement into the Definition Phase (Phase A). This phase includes a parallel competitive industrial definition team lead by two European prime contractors. The invitation to tender from industry was issued by ESA in May 2020 and its resolution should be announced in September/October 2020.

This paper presents Comet-I mission concept and discusses some of the technological challenges relevant to the exploration of Long Period Comets.

2. An F-Class Mission

The F-Class mission is the latest of ESA's mission categories from its Science Programme. In particular, F-Class stands for fast-track, which refers to the fast and flexible developmental pathway necessary in order to benefit from shared launch opportunities with its sister mission category the M-class, or medium size. The first F-class call was announced in July 2018*. 23 proposals were received covering different aspects of planetary science, astronomy and heliophysics [2]. After a two-stage review process, the final selection was announced in June 2019.

The boundary conditions of the first F-Class call defined a modest mission, with 150 M€ of Cost at Completion (CaC), to be launched together with ESA's 4th M-Class mission; the Atmospheric Remote-sensing Infrared Exoplanet Large-survey or ARIEL. The launch of ARIEL is schedule for 2028. Thus, the F class mission must be launch ready by 2027, following a short developmental programme of about 8 years.

Launch for the F-Class mission is provided at no-cost. However, the F-Class is only the secondary payload of the Ariane 6.2 tasked to deliver ARIEL mission into a free insertion transfer towards a large amplitude Sun-Earth L2 orbit (SEL2). This implies that; (1) the wet mass allocated to the F-class mission is modest and must be constrained by the leftover performance of Ariane 6.2's launch of ARIEL; and (2) the F-Class spacecraft will be commissioned into the same SEL2 orbit. The actual available wet mass was initially estimated as 1,000 kg, to be later modified in several occasions. The latest requirement for maximum allowed wet mass is of 750 kg, excluding launch adapter [3].

Comet-I mission concept is perfectly aligned to take advantage of all the unique features of the F-Class mission call. Firstly, the deployment of the spacecraft into a SEL2 orbit is ideal to depart towards heliocentric orbits at low Δv costs. Secondly, a SEL2 is an ideal position to be able to wait or idle with nearly negligible station-keeping manoeuvres. These are perfect features for a mission that proposes to visit a pristine yet-to-be-discovered Oort cloud comet. The ideal Comet-I target should be visiting the inner solar system for the first time. As such, it will be discovered only a few years before it reaches the periapsis, and thus only a launch-ready spacecraft could potentially intercept with it. Hence, having Comet-I awaiting for such an opportunity at the L2 point is a unique opportunity to explore objects of exceptional scientific value that have only a short timescale transit through the inner Solar System. This, of course, also potentially includes interstellar objects that may be discovered while Comet-I is on guard at the L2 point [4].

The F-Class call also encouraged missions capable of multi-point measurements by multiple spacecraft or smallsat configurations. Comet-I indeed envisages multiple spacecraft elements working together and collecting simultaneous data from several points and perspectives throughout the comet fly-by, which should result on a 3D reconstruction of the visited target.

Comet-I proposal was finally selected as the first F-Class mission in June 2019. This will be the first mission to be designed without an identified, or unknown, target. Comet-I architecture includes a main spacecraft (SC-A) that would make remote observations of the target comet from afar, and protect it from the dust environment while acting as the primary communications hub for the other two mission elements. Two smaller spacecraft, SC-B1 and SC-B2, would venture much closer to the target, carrying instruments to complement and enhance the scientific return from other mission elements. SC-A and SC-B2 will be delivered by ESA, while SC-B1 is delivered by JAXA.

3. Science Motivation

Comets are building blocks of our Solar System. After their formation on the outskirts of the protoplanetary nebula, they migrated into stable long-lived orbits, cold enough so that their original ices and volatiles were preserved. Comets we observe today must have been idling in these stable orbits for billions of years, until they were recently nudged out by perturbations, such as those from the Galactic tide, nearby stars and/or Solar System planets. There are three main known reservoirs of comets (i.e. long lived orbits): the main asteroid belt, home to the population of main belt comets (MBCs); the scattered disk beyond Neptune, source of the short-period Jupiter-family comets (JFCs); and, largest and least understood, the Oort Cloud, at tens of thousands of AU, source of the Long Period Comets (LPCs) and some Halley-type comets (HTCs).

So far, eight comets have been visited at close range. All of them short periodic comets from the scattered disk, except Halley. 1P/Halley was visited by an armada of six spacecraft in 1986. Among these, the first interplanetary spacecraft flown by the European Space Agency; *Giotto*. Comet Halley is most likely an Oort cloud comet, however it has suffered substantial surface compositional and morphological modifications due to its many passes through the inner Solar System. ESA's *Rosetta* mission visited instead Comet 67P/ Churyumov–Gerasimenko, a JFC. One of the highlights of Rosetta's visit to 67P is the confirmation of the extent to which the comet nucleus is altered by the multiple cycles of activity. This motivates the visit of a truly pristine Oort Cloud comet, which is hopefully visiting the inner Solar System for the first time.

Thus, the main aim of Comet-I is to visit and characterize an LPC that could potentially be dynamically new (i.e. reaching the inner Solar System for the first time). Given their exceptional scientific

* https://sci.esa.int/web/cosmic-vision/-/60498-call-for-a-fast-f-mission-opportunity-in-esa-s-science-programme

value, Comet-I may instead visit an interstellar object, if any such an object is discovered within the reach of the spacecraft, while awaiting at the L2 point. However, the probability of a reachable interstellar object being discovered is very low.

Comet-I will answer key questions such as *What is the surface composition, shape, morphology, and structure of the target object?* And *What is the composition of the coma, its connection to the nucleus (activity) and the nature of its interaction with the solar wind?* By doing so, Comet-I will broaden our understanding the evolutionary path of comets from their formation in the protoplanetary nebula. Ultimately, Comet-I seeks to bring new understanding of the working of our Solar System, the processes of planetary formation and the emergence of life.

4. Long Period Comets

Thus, the goal of Comet-I is to improve the understanding of the evolution of our Solar System by visiting one of its pristine building blocks. This will be on the form of a newly discovered Long Period Comet from the Oort cloud. These objects generally result on some of the most spectacular objects in our night sky due to their bright comas and tails (see Figure 1). Thus far, there has been 2668 LPCs discovered† (as of August 2020). The annual rates of discovery are currently about 30 LPCs a year (averaged for the last decade).

Figure 1. Comet NEOWISE C/2020 F3 was discovered in March 20202 and became visible to the naked eye in July 2020. Image credit: Kai Noeske (@kainoeske; 2020).

The only way for Comet-I to intercept an LPC is for it to be discovered sufficiently deep into the outer Solar System so that the spacecraft has sufficient warning time to make its way to the *closest* intersection point. All-sky surveys have seen an impressive transformation in recent years. Currently, the Pan-STARRS and ATLAS surveys of the northern sky provide routine detection of comets to 21st magnitude. As shown by Królikowska and Dybczynski (see Figure 2) [5], this improved survey capability has resulted into an increase of the distance at which these objects are discovered.

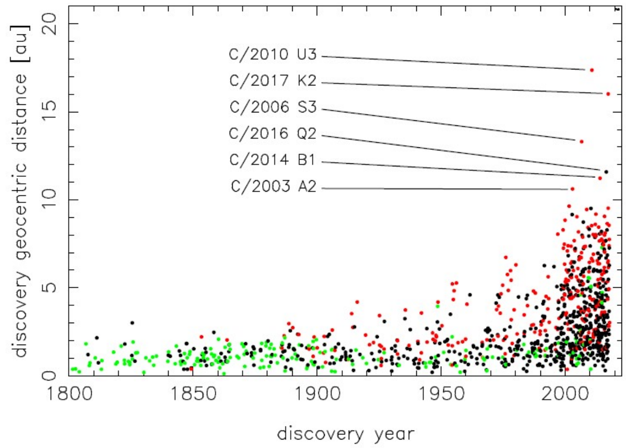

Figure 2. Discovery date and distance of LPCs until 2018. An increase of geocentric distance (and thus heliocentric as a consequence) can be clearly observed following advances in survey technology. Figure reproduced from Krolikowska & Dybczinski [5].

The Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) will soon follow with southern sky surveys at 24.5 magnitude. The LSST survey is schedule to be online from mid-2020s and will indeed conduct the most sensitive Solar System survey ever performed [4]. A survey simulation environment developed for LSST [6, 7] was used to simulate the detection efficiency of the synthetic LPCs generated by Boe et al. [8]. This simulation confirms that most of the LPCs discoveries are expected to have more than 3 years of warning time. In particular, 90% of the LPCs should be spotted beyond the orbit of Jupiter, 80% should allow for more than 2 years of warning time and about 75% should allow for more than 3 years of warning time [9].

5. Preliminary Mission Analysis

Needless to say, Comet Interceptor will not be able to rendezvous with an LPC, mostly due to the isotropy of its orbital velocity. Figure 3 shows an example of an intercept transfer to Comet C/2003 T4. This comet transfer serves well to illustrate the impossibility to rendezvous with it, since, given its inclination (i~87°), the relative velocity of the encounter is of 55 km/s. Rosetta mission did manage to rendezvous with 67P [10]; however, the large relative velocity of LPCs (caused by their nearly isotropic orbit orientation), as well as a shorter mission duration for Comet-I and a more limited Δv capability, makes a rendezvous transfer

† Data was downloaded from JPL Small-body Database. The list includes all P>200 years, hyperbolic and parabolic comets with q<10 au.

not a feasible option. Hence, Comet-I will necessarily need to aim for a flyby to a recently discovered LPC.

Comet C/2003 T4 was discovered in October 2003 by the LINEAR survey. The trajectory presented in Figure 3 would have required for Comet-I to depart in February 2003, in order to intercept with Comet C/2003 T4 in April 2005. However, a survey with the capability of LSST would have likely observed the comet years earlier [11], thus enabling this transfer. Lastly, Comet-I is also severely limited in Δv capability, as a consequence of its limited wet mass (i.e. shared launch) and cost cap. The expected Δv capability is estimated about 750 m/s if a chemical configuration is used or 1.5 km/s if a low thrust or hybrid system propulsion system is used. However, given the constraints on the costs and development, the chemical configuration seems to be preferred [1]. Given these limitations, the heliocentric cruise is a relatively simple affair, with a direct transfer Earth to an intersection point in the LPC orbit near the ecliptic plane.

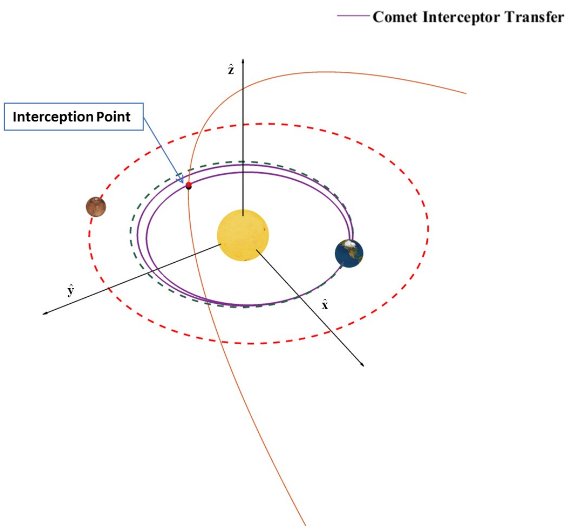

Figure 3. Example of Comet-I fly-by Transfer. Hypothetical interception of Comet C/2003 T4 (LINEAR).

Figure 4 shows Comet-I's region of accessibility in the ecliptic plane. These regions are plotted in a synodic reference frame, i.e., a reference frame rotating with the Earth. Four distinct capabilities are plotted: Δv as 0.5, 1, 1.5 and 2 km/s. The transfer cost to each point in the synodic reference frame is computed as simple multi-revolution lambert arc whose time of flight has been optimised to minimize Δv costs. The upper bound for the time of flight is 3 years. The figure also shows all the nodal points (i.e. ascending and descending nodes) of the known LPCs, within 1.5 au. Finally, the accessible area has been limited within the heliocentric radius region between 0.9 to 1.25 au. This comes as a thermal design requirement as discussed in ESA's CDF study [1]. ISEE-3/ICE also had a similar heliocentric distance limitation due to thermal and power constraints [12].

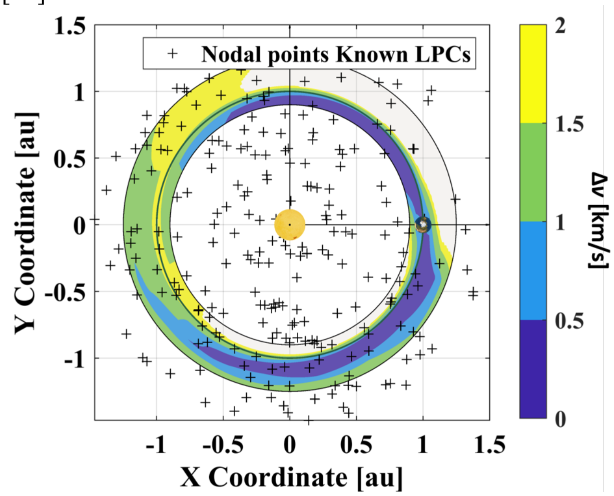

Figure 4. Accessible regions in the ecliptic plane as a function of different spacecraft's Δv capabilities.

The decade 2010-2019 saw a total of 21 new LPCs with a nodal point within the accessible range [0.9,1.25] au; i.e. 2.1 LPCs a year. As shown in Figure 4 and as discussed further in Sanchez et al [13], the intersection point for these comets can be anywhere in the plotted accessible region between 0.9 to 1.25 au. According to ESA, the mission duration should be less than 6 years [3]. Following the latter, a Monte Carlo simulation can be generated to estimate the probability of succeeding to complete the mission within a given mission duration. Each Monte Carlo simulation generate an annual average set of 2.1 LPCs, with random intersect points in the accessible region of the ecliptic plane. A warning time is also allocated to each randomly generated LPC, based on the results of an LPC detection efficiency analysis of the survey simulation environment developed for LSST [6-9]. A transfer can then be optimized given the available warning time. This Monte Carlo Analysis allows to extract a reliable measure of the probability to complete the mission within an allocated mission timespan. The results of this analysis are summarized in Figure 5.

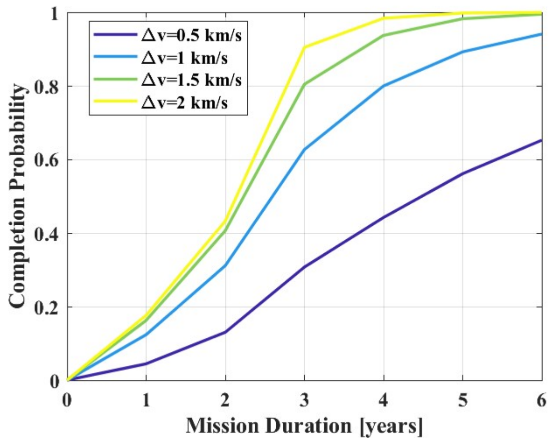

Figure 5. Probability of Successful Comet-I mission within an allocated mission timespan and Δ*v* budget.

The dynamical model for the transfers used for Figure 5 assume a patched-conic approximation with a departure from the Sun-Earth L2 point. However, Comet-I departure conditions will be from a large amplitude SEL2 quasi-halo orbit, rather than the L2 point itself [14]. This in fact implies larger escape velocities than those generated by departures from the L2 point. Similarly, Comet-I could also benefit from a lunar fly-by, particularly for interception transfers towards Earth-leading configurations [15]. Both of these considerations imply that, while the Δv capability for Comet-I is of 750 m/s, the actual equivalent Δv performance for Figure 5 should be in the range of 1 to 1.5 km/s.

Hence, the results in Figure 5 demonstrate that Comet-I has indeed very good prospects to be completed successfully within 6 years from launch. However, in the unlikely event that no accessible LPC is found during the allocated waiting time in L2 (~3 to 4 years), then the Comet-I science team has identified a list of potential backup short period comets as alternative targets [14, 16].

6. Space Segment

Comet-I's baseline is to visit a yet-to-be-discovered long-period comet with three spacecraft elements. The main ESA-provided spacecraft A will make remote observations of the target from afar (≥1,000 km), to protect it from the dust environment. Two smaller spacecraft elements (B1 provided by JAXA and B2 provided by ESA) will be separated from spacecraft A up to several days before the comet encounter and will venture much closer to the comet (<500 km), carrying instruments to complement and enhance the scientific return of Comet-I. Spacecraft A will act as primary communications hub for both spacecraft B1 and B2.

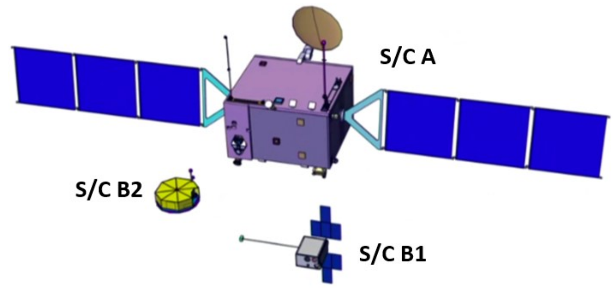

Figure 6. Comet-I Concept Design for Illustration only. Courtesy of ESA CDF Phase 0 analysis [1].

Figure 6 shows the design concept resulting from ESA's CDF study [1]. The design has actually changed substantially from its first iteration previous to the proposal submission, and it is likely to continue changing during the Industry Definition Phase (phase A). As currently stands, the wet mass for spacecraft A is likely to be just under 700 kg, while spacecraft B1 and B2 will be 30 kg each [3]. Comet-I will carry a total of 10 scientific instruments to perform comet nucleus and environment science [17]. Table 1 provides a short summary of the instruments in each spacecraft.

Table 1. Summary of scientific instruments in Comet-I.

SPACECRAFT	INSTRUMENT	DESCRIPTION
ESA S/C A	CoCa	Visible Camera
	MANIaC	Mass Spectrometer
	MIRMIS	NIR/Thermal IR Imager
	DFP	Dust, Field & Plasma
ESA S/C B2	EnVisS	All-sky multispectral imager
	OPIC	Visible imager
	DFP	Dust, Field & Plasma
JAXA S/C B1	HI	Hydrogen Imager
	PS	Plasma Suite
	WAC & NAC	Wide and Narrow FOV cameras

7. Conclusions

Comet-I is a newly selected ESA mission in its early definition phase (Phase A). Following on the heritage of Giotto and Rosetta Missions, Comet-I will visit a pristine long period comet in order to provide further understanding of the cometary evolutionary pathway. By definition, long period comets that have not undergone multiple cycles of activity (i.e. pristine) must be unknown to our comet catalogues, either because they are indeed arriving for the first time to the inner Solar System or because no astronomical record can possibly exist of a previous passage. Hence, all-sky surveys, such as the soon-to-be-operational LSST survey, play the key role to spot any new LPC with sufficient warning time for Comet-I to reach it.

Comet-I spacecraft will be launch and deployed in the Sun-Earth L2 point in 2028, together with ESA's ARIEL mission. There it will remain until an LPC intercept opportunity becomes available. While the mission concept may appear chanceful, a preliminary Monte Carlo analysis of statistical LPC opportunities demonstrate a low risk of having no fly-by option during the 6 years of mission duration. The Monte Carlo analysis also shows a median mission duration of only 3 years. However, in the unlikely event that Comet-I is not bestowed with an opportunity to visit an LPC, a number of unique science opportunities are also identified to visit known short period comets.

Comet-I is the first of ESA's F-class mission: a new science driven mission class, with emphasis also on novel mission implementation that can benefit from shared launch opportunities with the M-class mission. Comet-I is the first mission to be designed and, possibly, launched without an identified target. Such a mission concept may also serve as a model for other mission types such asteroid deflection missions or a fully dedicated mission to explore an interstellar object.

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Sánchez, Joan-Pau