RAPID RECONNAISSANCE MISSIONS BASED ON ESA'S COMET INTERCEPTOR Colin Snodgrass[1], Geraint H. Jones[2], Cecilia Tubiana[3], [1]University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, U.K.; csn@roe.ac.uk; [2]Mullard Space Science Laboratory, University College London, UK; [3]INAF - Istituto di Astrofísica e Planetologia Spaziali, Rome, Italy

Keywords: *Mission design, reconnaissance, asteroid characterisation*

Comet Interceptor:

Comet Interceptor (CI) is a mission led by the European Space Agency (ESA), with a significant contribution from the Japanese Space Agency (JAXA), that will perform the first in situ investigation of a Long Period Comet (LPC). As LPCs are typically only discovered a few months prior to their closest approach to the Sun, and do not return for many thousands of years, a mission to one relies on designing, building, and launching the spacecraft before its target is known. CI will take advantage of the increased distance at which comets are discovered by modern survey telescopes (expected to significantly increase with the beginning of the Vera C. Rubin Observatory's Legacy Survey of Space and Time in 2025) to target a newly discovered comet found a few years prior to its perihelion. While this is not long enough to plan and build a dedicated mission, it is long enough to reach the necessary encounter point from a waiting position in space. CI will wait in a halo orbit around the Sun-Earth L2 point, taking advantage of a shared launch with the ESA Ariel space telescope that will operate there. It is expected to launch in 2029, and can wait for a few years for a suitable comet to be found, with an expected comet encounter in the mid 2030s [1]. The mission was selected by ESA in 2019, and is now in phase C, having passed mission adoption in 2022. It will be built by a consortium led by OHB (fig. 1).

CI will be the first mission to launch before its target is known. This presents some challenges in mission design, primarily because the trajectory, and therefore required Δv and fuel mass, are not fixed. The mission is therefore designed in as generic way as possible, with broad constraints on target choice that allow design choices to be made while maximising the number of possible comets that could be reached. Maximising the flexibility of the mission (within a set maximum duration of 6 years due to the funding envelope of the ESA F-class) means maximising the amount of the mass budget dedicated to fuel, but this obviously has to be traded against other demands on spacecraft mass, e.g. payload, spacecraft systems, and, in the case of a comet mission, the dust shield required to protect against high velocity impacts.

Figure 1: Artist's impression of a preliminary design of the CI spacecraft (courtesy of OHB).

In order to demonstrate mission feasibility, analysis of the range of possible comet encounter locations was performed [2]: LPCs can have highly inclined orbits, but feasible encounters must happen near the ecliptic plane. For thermal design reasons, we limit the range of heliocentric distances the spacecraft will operate in to 0.9–1.2 au. Thus the potential encounter space is defined as a torus in the ecliptic between these distances, and potentially feasible comets are those with node crossings within this range – with a strong preference for comets on their inbound leg, to avoid additional uncertainties in their predicted position post-perihelion due to non-gravitational forces. How much of the torus can be reached is a function of available Δv and the length of the interplanetary cruise – which is set by the warning time expected between target discovery and encounter date. For the expected mass budget available to CI (still uncertain at this time due to the untested performance of the Ariane 62 launcher that will be used), and the maximum 3–4 year cruise that will fit within the mission timeline and expected warning time for comets, we can reach the majority of the torus and find a high probability of a suitable comet being reachable in time [2]. More detailed analysis of predicted performance of the LSST in discovering distant comets, and hence the expected warning time, is ongoing. It is worth noting that the use of the Lagrange points as a stable waypoint on the way to a comet in some ways replicates what was done with the *ICE* mission in the 1980s, where a

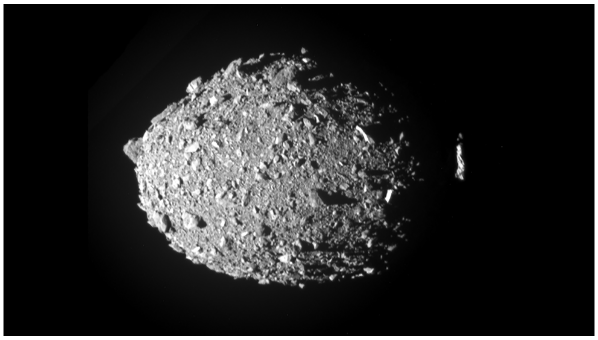

Figure 2: Image of asteroid Dimorphos from the DART mission [NASA/Johns Hopkins APL].

Solar Wind monitoring mission that had been operating at the Sun-Earth L1 point was redirected to perform fly-bys of comets Giacobini-Zinner and Halley [3]. The use of lunar fly-bys can give a significant 'free' boost to Δv when departing the Lagrange points, for suitable encounter locations.

Application to Planetary Defence:

A similar mission architecture could be of use for planetary defence as a way to obtain rapid reconnaissance of a newly-discovered hazardous asteroid. A spacecraft waiting in space could obtain resolved images and other in situ measurements of an asteroid within a year or two of discovery, depending on its orbit and the necessary transfer time; this would be significantly quicker than any new mission could be developed and launched.

The successful DART mission shows that small asteroids can be deflected, and that the momentum enhancement factor β was high for the case of Dimorphos [4], which appears to be a rubble pile in images obtained by DART on approach (fig. 2). For the purposes of planning a deflection mission, it could reasonably be expected that an impact with a similar asteroid might also produce a similar β. Reconnaissance observations ahead of any deflection attempt would be valuable: even simple monochromatic imaging would at least allow a first comparison with DART images of Dimorphos, and an assessment of e.g. surface boulder size distributions, which would be relevant for predicting the likely effect of an impact.

Where warning times before a potential impact are measured in years rather than many decades, the advantage of being able to obtain reconnaissance images relatively quickly by using a CI-like concept would greatly enhance the possibility of success of subsequent deflection missions. Relatively small and simple spacecraft, potentially even CubeSats, could be used for asteroid reconnaissance, compared with the more complex needs of CI as a comet science mission. As the primary limitation on how quickly the mission could reach a suitable fly-by would be on Δv, there is a clear trade to be made between very small spacecraft with limited manoeuvring capabilities and larger ones with more fuel. Another key design driver may be how robust the components are to a prolonged wait in space, which may become a cost driver. Longer-lived spacecraft that could wait for decades may not be cheaper than simpler ones that are replaced if not used within a certain lifetime (and in reality, such spacecraft could likely be targeted to a non-threatening asteroid for scientific purposes as they approach the end of their usable lifetimes). Since the use of waypoints such as the Lagrangian points offers a lot of flexibility in terms of launch time, missions using this concept have an inherently adaptable launch window, and can take advantage of suitable ride-share opportunities, greatly reducing their cost compared with a dedicated launch for a reconnaissance mission.

Payload:

CI is designed to study a comet, including in situ sampling of its gas, dust and plasma environment as well as multi-wavelength remote sensing cameras. It includes two releasable probes that will perform closer fly-bys of the nucleus than the main spacecraft, which will maintain a safe distance from the hazardous inner coma. A mission dedicated to a first-look characterisation of a potentially hazardous asteroid could be significantly simpler, comprising a single spacecraft without the need for dust shields, and with a simplified remote sensing payload. Of the CI payload, the most useful instruments for characterising an asteroid will be the primary imaging camera CoCa and the multispectral camera MIRMIS, which includes thermal infrared observations. This payload would enable morphological assessment (e.g. bulk shape and surface particle size distributions), compositional measurements (approximate mineralogy), and for thermophysical models of the surface's response to sunlight to be developed. A mass measurement may also be possible by radio science tracking of the spacecraft, should the asteroid be sufficiently large and/or the closest approach distance be small enough. These would be critical inputs to any mitigation mission.

The CoCa camera (University of Bern) is a large instrument (~ 13 kg) based on the CaSSIS camera on ESA's ExoMars Trace Gas Orbiter (fig. 3; [5]), adapted for CI to include a filter wheel for broadband imaging in four visible/near-infrared bands.

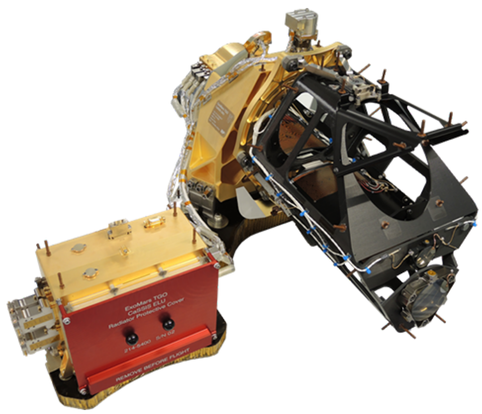

Figure 3: CaSSIS instrument on ESA ExoMars TGO, on which CI CoCa is based [Uni Bern].

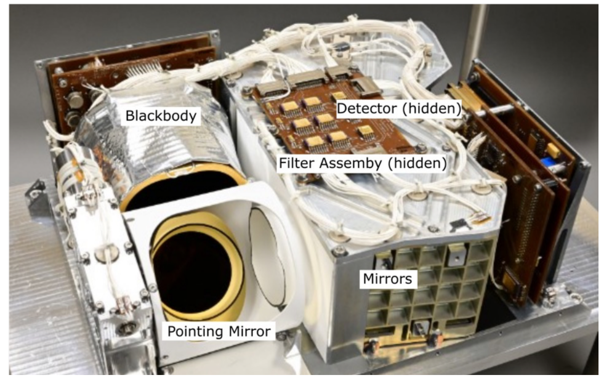

Figure 4: The Lunar Thermal Mapper instrument, similar to the thermal infrared channel of MIRMIS [University of Oxford].

The choice of a telescopic camera for the mission was driven by the need for the main CI spacecraft to perform a relatively distant fly-by at around 1000 km distance, and the scientific need to obtain images with resolution of approximately 10 m, for comparison with earlier comet fly-by missions. An argument could be made to use a telescopic camera like CoCa to achieve reasonable resolution at a relatively distant fly-by for a first reconnaissance mission to a recently discovered 100 m scale asteroid, whose orbit might not be known well enough to precisely target a much closer fly-by. We assume, however, that any asteroid posing sufficient threat to warrant a mission will have been the target of a significant campaign of precision astrometry for orbit improvement, and a much closer fly-by could be assumed. The use of a CoCa-like camera could achieve even better resolution (submetre) with a closer fly-by of an asteroid, or a simpler (and smaller/cheaper) camera could be used to get comparable resolution.

A multispectral camera like MIRMIS (University of Oxford, [6]) would greatly enhance an asteroid mission by allowing more detailed characterisation of composition and/or thermal response, giving information that will be comparable to the expected Hera results at Didymos/Dimorphos [7]. MIRMIS is modular, covering near-, mid- and thermal-infrared wavelength ranges. The thermal camera is based on the Lunar Thermal Mapper instrument on NASA's Lunar Trailblazer smallsat mission – a standalone CubeSat-scale camera with its own scanning mirror and onboard calibration source (fig. 4; [8]) – while the shorter wavelength section is closely related to the ASPECT instrument on the ESA Hera mission's Milani CubeSat [9]. This instrument could be included in a relatively simple spacecraft, even a CubeSat-based design, to enable rapid and relatively cheap reconnaissance. While the spatial resolution achieved by MIRMIS is lower (by around an order of magnitude) than CoCa, one could achieve similar goals using only the shorter wavelength imaging channel of MIRMIS with a closer approach, to have a single (CubeSat-sized) instrument mission. For an asteroid mission, the instrument could be further simplified by omitting the mid-infrared (2.5–5 μm) spectroscopic channel of MIRMIS, which is primarily focused on characterising gas emissions in the cometary coma, although retaining this capability would add an interesting option to search for any weak outgassing, and therefore indications of ice content, in the target asteroid. As recent results show that there may be a considerable number of 'asteroids' which have a cometary origin and buried ice [10], and therefore significantly different bulk properties relevant to any deflection attempt, such a capability is definitely worth considering.

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