DIVERSITY: A MISSION CONCEPT FOR A GRAND TOUR OF MULTIPLE ASTEROID SYSTEMS.

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Introduction: Multiple Asteroid Systems are a relatively new category of Small Solar System Bodies (SSSBs) since the discovery of Dactyl, companion of (243) Ida, in 1993. Today, the Virtual Observatory Multiple Asteroids Database (VOMAD) [1] contains a list of ~203 asteroids known to possess a companion from every population of SSSBs in the solar system. Despite years of observations using mostly ground-based telescopes, it remains unclear how these multiple asteroid systems form and evolve. However, it is clear that they played a key role in the formation and evolution of our solar system and contain important information about the early life of our solar system.

For instance, recent work by [2] clearly suggests that small binary systems in the NEA and main belt populations are formed by the YORP effect [3] and can quickly become unstable. The process of fissioning and splitting is very likely the dominant way for small asteroids to lose mass, rather than via collisions. In the outer part of our solar system, a large fraction of 100-km class low-inclination objects in the Kuiper Belt are known to be binary systems. Nesvorny et al. [4] found that these binaries could have formed during gravitational collapse when an excess of angular momentum prevented the agglomeration of all available mass into a solitary object.

The multiple asteroid systems are also unique natural laboratories for studying surface modification processes (space weathering, impacts, shattering) on asteroids since the populations encompass a large range of compositions, sizes, shapes, densities, environments and histories. Understanding these fascinating and unknown worlds could be greatly facilitated by *in situ* observations by a spacecraft. Special care is needed, however, due to technical challenges concerning spacecraft safety and navigational complexity in multiple asteroid systems.

Propulsion system and Trajectory: We developed a mission concept allowing us to explore several multiple asteroid systems by successive rendezvous. We chose the NEXT engine, a reliable and flexible propulsion system for this kind of mission concept. Several possible trajectories, including flybys and rendezvous with multiple asteroid systems, were found. Figure 1 shows a low cost option, which begins with a flyby in Oct. 2017, 10 months after launch, of 3169 Ostro [5], a small close-contact asteroid. This is followed by a 120-days rendezvous in Aug 2020 with (3749) Balam, a young and puzzling S-type triple system. A second rendezvous with (45) Eugenia and its two moonlet satellites [6] is scheduled from March to July 2024. The mission ends with a rendezvous at (90) Antiope, a uniquely large double asteroid, in May 2029. A trajectory including the similar flyby sequence (Balam, Eugenia, Antiope) was found with a launch scheduled in Dec 2018. We are currently searching for a potential NEO flyby for this trajectory.

Instruments and Science goals: Thanks to its flexible propulsion system, the spacecraft should be able to approach each component of the multiple systems to within 5 km. The scientific payload will be relatively simple and will consist of:

- a visible WAC and a NAC camera
- a low-resolution visible and NIR spectrograph
- a low-resolution mid-IR spectrograph
- a LIDAR instrument

These instruments will help to provide direct insights into i) the formation and evolution of multiple asteroid systems, ii) the diversity in composition of the main belt, iii) the thermophysical properties of asteroids and the influence of YORP.

Target Summary: This mission provides the opportunity to study a diverse sample of four main-belt multiple asteroid systems.

• **Diversity in composition**
- 3749 Balam is a S-type
- 45 Eugenia and 90 Antiope are C-type
- 3179 Ostro is a X-complex asteroid (E or M type)

• **Diversity in multiplicity**
- 1 triple asteroid with 2 moons (45 Eugenia)
- 2 doublet asteroid systems - a large and unique one (90 Antiope) and a small one (3169 Ostro)
- 1 loosely-bound binary

• **Diversity in size**
- 3749 Balam D_1=2.4 km, D_2=6.1 km, D_3=3 km
- 90 Antiope $D_{components}$~85 km
- 3169 Ostro $D_{components}$~1-2 km
- 45 Eugenia $D_{primary}$~195 km, $D_{satellites}$ = 5-10 km

• **Diversity in their estimated age**
- 3479 Balam: very young system <500 kyrs
- 90 Antiope: very old system, 1-3 Byrs, member of the Themis family
- 45 Eugenia, 3169 Ostro: age unknown

• **Diversity in distance to the Sun**
- 3169 Ostro: at 1.8 AU
- 90 Antiope: at 3.6 AU

Stable spacecraft orbits: This space mission concept requires the identification of safe orbits for the spacecraft. Due to communications limitations and uncertainties in system properties, selected orbits must be stable under small variations in the spacecraft's position and velocity. To identify such stable regions, we developed a Monte Carlo simulation to test a large selection of orbits around the components of several multiple asteroid systems. The algorithm numerically integrates Newton's equations of motions for the sun, the components of an asteroid system, and a spacecraft. It incorporates rigid point structures to model the extended shapes of asteroid components, and includes the effects of solar radiation pressure on the spacecraft. With ~120 days expected for scientific orbits in each asteroid system, we searched for orbits around each component exhibiting at least 20 days of stability. Orbits were judged to be stable if, after 20 days, the spacecraft neither impacted the target asteroid nor strayed further than 5 times its initial distance from the target asteroid ("ejection"). The time of impact/ejection was recorded for unstable orbits; the orbital eccentricity was recorded for stable orbits.

A run of ~13,000 orbits around the moonlet Petit-Prince in the 45-Eugenia system is shown in Figure 2. The simulation was constructed using orbital parameters derived by F. Marchis et al. [6]. The initial positions of stable orbits are indicated in green, impacting orbits in red, and ejecting orbits in blue. The spacecraft initial motion is retrograde, out of the depicted plane, where the z-axis is perpendicular to the orbital plane of the moonlet around the primary. The dot size is proportional to the initial velocity, which is chosen from a normal distribution about the Keplerian velocity with a 1-sigma of v_{kepler} / 6. The moonlet's estimated radius (~3.5 km) is indicated in black. The plot indicates instability at the extrema of initial velocity and near the moonlet's poles. A "cone of stability" is apparent from our simulations, allowing the spacecraft to be stable at less than 1 km from the surface near the equator of the moonlet. Future work involves investigating the effects of modifying the mass distribution in the primary, the configuration of the moonlets at the time of the injection of the spacecraft, and the size of the moonlets on the stability results. We will also extend our simulations to include other multiple asteroid systems.

References:[1] VOMAD http://cilaos.berkeley.edu/PHP_scripts/VOBAD/VOBAD_portal.html [2] Pravec, P. et al. (2009) Nature 466 1085. [3] Cuk M. (2007) *ApJ 659*, 1, L57-L60. [4] Nesvorny et al. (2010) *AJ 140*, 3, 785-793. [5] Descamps et al. (2009) Icarus 189 [6] Marchis, F. et al. (2009) *Icarus 210*, 2, 635-643

Additional Information:

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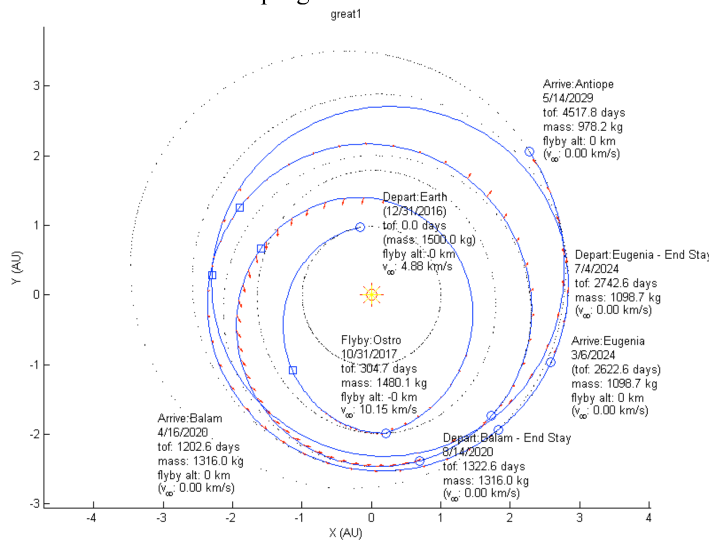

Figure 1: Possible trajectory of the mission allowing to visit 4 MB multiple asteroids (Ostro, Balam, Eugenia, Antiope) over 16 years.

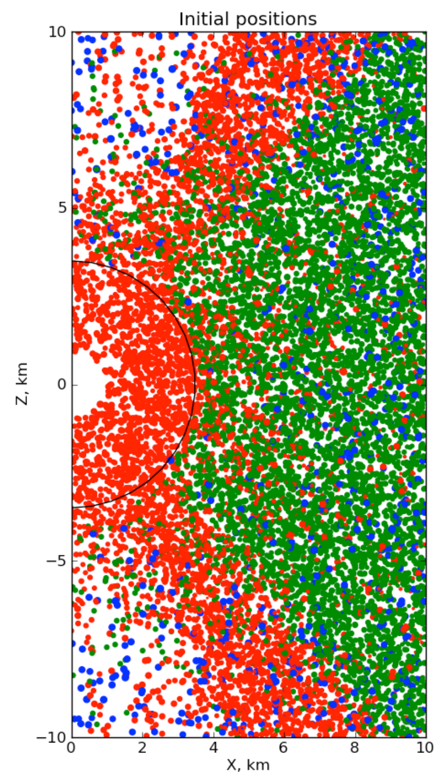

Figure 2: Search for safe orbit around Petit-Prince, one of the satellites of 45 Eugenia, by Monte-Carlo simulation (see text).