4th IAA Planetary Defense Conference – PDC 2015
13th-17th April 2015, Frascati, Roma, Italy

IAA-PDC-15-P-69

CASTALIA PROPOSAL: EXPLOITING A SCIENCE MISSION FOR ASTEROID DEFLECTION

A. Gibbings(1), M. Homeister(1), the Castalia CE Study Team(2), Castalia Science Team(3)

(1) OHB System AG, Universitätsalle 27-29, 28359 Bremen, Germany,
+49 421 2020-7461
+49 421 2020-9733
(2) OHB System AG, DLR and various research institutes
(3) Various international research institutes

Keywords: *Main Belt Comet, asteroids, sublimation, deflection, demonstration,*

ABSTRACT

The Castalia mission aims to explore and characterize the Main Belt Comet (MBC) 133P/Elst-Pizarro. MBCs are a new class of solar system objects that span the divide between the tradition definition of asteroids and comets. They reside in the main asteroid belt but display a comet-like appearance at certain points in their orbit. The mission would there provide a unique insight in early planetary formation and the interaction of water and organic compounds throughout the asteroid belt and with Earth. Science data is gained through ten on-board remote sensing and in-situ instruments. Measurements includes, but is not limited to, the emission of gas and dust, flux, momentum, inferred composition and bulk density. These measurements are also directly applicable to further understanding the chemical and physical properties of solar sublimation and laser ablation. Both these approaches have been proposed as possible low thrust asteroid deflection techniques. Data will detail the mass flow, expansion and velocity of the sublimated material, the temperature profile and the occurrence of any deposition and degradation caused by the sublimated material. The latter, for example, can assist in improving the engineering and contamination models for spacecraft design. This paper will therefore presents an overview of the Castalia mission, including its science objectives and system design. It will then explore how the results and technological advances of its mission scenario and payload design can be applied as a stepping stone for planetary defense activities, specifically laser ablation and solar sublimation.

INTRODUCTION

The Castalia mission was recently proposed for the next ESA M4 Medium Class mission call [Jones et al, 2015]. Intended for launch in 2025+ the call was open to all areas of space science that are related to the science goals and questions described in ESA's Cosmic Vision plan [ESA, 2014]. The call also favored the use of a European procured launcher (Vega or Soyuz), a relatively fast development schedule and a targeted cost at completion of 450 MEuro (including all nominal operations in FY2014 economic conditions). International collaboration could have also been considered, but with no more than an 80%-to-20% share.

The mission aims to explore and characterize a Main Belt Comet (MBC) – 133P/Elst-Pizarro. MBCs are a new class of solar system objects that straddle the divide between volatile-poor asteroids and violate-rich comets whose primary reservoir lies far from the Sun. MBCs are characterized as objects that reside within the asteroid belt, but have a comet-like appearance with a dusty comae and tails at certain periods in their orbits. This therefore challenges the traditional definition of asteroids and comets, the formation and early evolution of the main asteroid belt, and the origins of water on Earth. The instrument science data gained from the mission is also applicable for an analogue demonstration of asteroid deflection techniques, namely ablation by solar sublimation or a laser.

The driving mechanism behind the repetitively observed activity on MBCs currently favors the water-ice sublimation of a (sub)surface frozen reservoir. Material is ejected to form a coma and tail as on standard comets. Reservoirs are either located near the surface, which can be initiated and sustained from solar heating, or are deeply situated beneath an insulated inactive later. An impact event, for example, exposes the underlying material and triggers the sublimation activity. On average, a collision event occurs somewhere in the main asteroid belt once every 1-10 years [Bottke et al. 1994; Jewitt 2012; Hsieh 2009; Capria et al 2012]. Examining the active and inactive phases of the MBC should therefore enable the distinction between any illumination- and heating-induced sublimation events. To address these issues, the high priority science of goals of the mission include:

I. The characterization of a new family of solar system objects by in-situ investigation
II. Understanding the physics of the sublimation activity
III. The direct detection of water in the MBC
IV. Testing whether MBCs are a viable source of water on Earth
V. Using MBCs as tracers for planetary system formation and evolution.

The paper will therefore demonstrate how, through science utilization data, a mission primarily developed for planetary science can also offer opportunistic potential to further the current understanding of possible deflection techniques. The mission and system design was performed by a consortium of OHB System AG, DLR Institute of Space Systems and an international team of scientists using concurrent engineering techniques. Castalia is presented as a fully funded ESA-only mission (optional international collaboration), with all scientific instruments supplied by a nationally-funded consortia.

CASTALIA MISISON

Described further on a (sub-)system level in [Homeister et al, 2014], the Castalia mission is intended to be launched in 2024 (2026 backup) on-board a Soyuz/Fregat from Kourou. It is a three-axis stabilized spacecraft, powered by deployable solar arrays and onboard batteries. An electric and chemical propulsion system is used during the interplanetary transfer and close approach operations at the target (including attitude control and reaction wheel desaturation) respectively. The navigation system uses a wide- and narrow- angle camera, LIDAR, IMU, star trackers and sun sensors. Thermal control is achieved through passive and active methods, including optical solar reflectors, radiators, multi-layer insulation, heaters and thermistors. Doublers provide thermal distribution. A large high-gain antenna and high-power travelling wave tube amplifiers (TWTA) provide a communication link through ESA's Deep Space Antennae ground station network (New Norcia, Cebreros and Malargue). X-band is proposed for telemetry up- and down-link, and Ka-band for science data downlink only. The onboard data-handling system generates telemetry, processes telecommands and monitors the spacecraft's status. It also acquires and stores the on-board data before downlink. Medium- and low-gain antennas are also used during the early mission phase and in emergency cases respectively.

Following a 4.5 year interplanetary cruise the spacecraft would arrive at 133P/Elst-Pizarro several months before its estimated reactivation, and be followed by a dedicated science phase. 133P/Elst-Pizarro was selected as it has a proven repetitive and periodically observable level of activity. As shown in Figure 1, it has a detectable tail for approximately a year of its five-year orbital period. Activity starts one month before perihelion and has occurred over four revolutions since its discovery. This provides continued evidence of its sublimation driven activity.

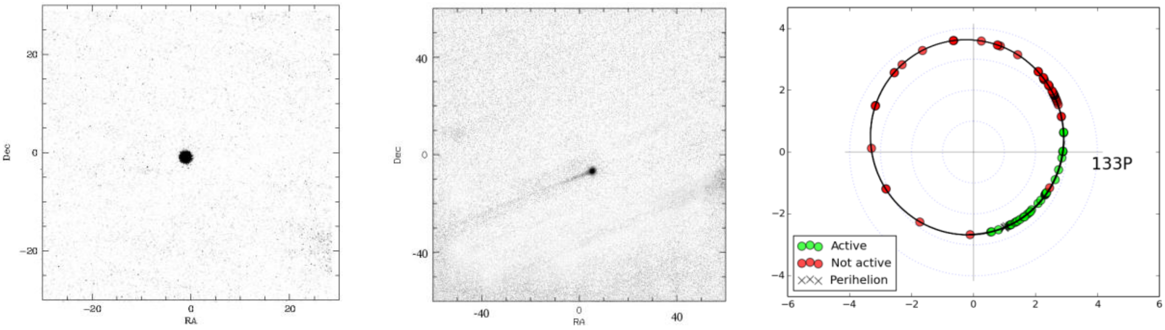

Figure 1: Comet 133P/Elst-Pizarro near aphelion (Jan 2010, ESO NTT), around perihelion (Sept 2013, ESO NTT) and the top view of the orbit. The symbols in the far right indicate the MBC's position during observations over four consecutive orbits.

133P/Elst-Pizarro has a radius of approximately 1.9 km, a density of 1000 kg/m^3 and a short spin-period for a comet of only 2.5-3.5 hours [Hsieh et al, 2009]. It is therefore expected to be a loosely bound rubble-pile asteroid, rather than a solid structure of rock and ice. The fast rotation requires a higher density, with a larger rock-to-ice ratio, but it still has a density much lower than most asteroids. Its low orbital inclination also contributes to a favorable transfer and rendezvous approach. However, since the search for MBCs is currently ongoing, further targets maybe identified that provide a simpler mission profile with reduced complexity and improved access. Other considered targeted have included 2380/Read (current back-up), 2005 VW139 and P/2012 Ti Pan-STARRS. These were less compatible to the M-class mission constraints and launcher performance.

Upon arrival at the MBC, the spacecraft will perform a series of far- and close-approach manoeuvers. Different distances allow global and local characterization, as well as long-term in-situ analysis. It is critical that the mission sequence adheres to the needs of the payload and their required measurement duration. During the far approach the spacecraft enters a heliocentric orbit approximately 1000 km away from the target. The distance is then reduced to 100 km as the spacecraft starts global characterization. Observations include medium-resolution shape models, surface scattering, temperature, interaction with the solar wind and the first signs of any weak sublimation activity. The main MBC science phase begins at approximately 20 km from the target as the spacecraft is inserted into an orbit around the target. This enables high-resolution shape models, temperature maps and surface mineralogy to be determined before the onset of any activity. A series of dedicated hovering maneuvers, where the relative distance between the spacecraft and the MBC reduces to approximately 5 km, occurs with the onset of activity. As the spacecraft periodically approaches the surface, the MBC rotates underneath. This enables the spacecraft to repetitively pass through and be exposed to the emission cone. Direct measurements of the sublimated gas and dust are performed. Data includes the isotopy of the water gas, the characterization of the plasma environment, the temperature of the local surface region and the magnetism of the surface and structure. Reported in Table 1, ten remote sensing and in-situ instruments operate throughout each mission phase, providing:

- Confirmation of the impact-activation theory by identification of a possible impact site
- Mapping of the surface structure, geology and hydrated/organic minerals, and search for ices
- Determination of the elemental and molecular dust composition, structure and size distribution, and comparison to comets and asteroids

- Determination of the elemental and molecular abundances or sensitive upper limits of volatile species
- Determination or constraining of the subsurface and internal structure
- Characterisation of the diurnal and orbital activity cycle
- Characterisation of the plasma environment of a weakly outgassing object and its solar-wind interaction
- Search for a primordial inherent magnetic field in a small solar system body
- Determination of the global physical properties, including its mass, volume, gravity field and thermal properties
- Determination of the deuterium/hydrogen ratio and isotopic composition

Table 1: Proposed instrument activity during the different mission phases.
The dark grey areas denotes the required and the light the optional (desired) science operations

	Instrument	**1000 km**	**100 km**	**20 km**	**5 km**
Remote Sensing	Visible & NIR Spectral Imager	x	x	x	x
	Radar (deep interior)			x	
	Radar (shallow subsurface)			x	
	Thermal Infrared (IR) Imager		x	x	x
	Radio Science			x	
In-situ Payload	Dust Impact Detector			x	x
	Dust Composition Analyzer			x	x
	Neutral/Ion Mass Spectrometer			x	x
	Magnetometer	x	x	x	x
	Plasma Package	x	x	x	x

The imagers, radars, mass spectrometer and dust composition analyzer have been identified as key instruments for achieving the main mission goals and objectives. These instruments, excluding the radar, also provide cross-over into planetary defense activities. It is achieved, as discussed later, by the determination of the MBC's shape, composition and albedo, and the spectral-thermal analysis of the sublimated material through secondary global mineralogical and compositional analysis. The scientific return of the mission could also be extended by investigating the formation of the tail and possible end-of-life landing attempt (similar to the NEAR Shoemaker mission at Eros and using heritage gained from the Philae landing). These two optional extras are not included in the current baseline. No additional resources or costs have been assigned. Current end-of-life operations include the cut-off of communication. The heliocentric orbit is far from Earth and other planets, and there are no planetary protection issues.

INSTRUMENT SELECTION

Payload instrument selection was based on the ability to achieve the scientific objectives, mission feasibility and the system-level drivers relating to mass, power, data generation, accuracy and duty cycles. The scientific camera package for Castalia includes a high-resolution visible imaging camera (based on the DAWN framing camera) and a wide-angle imaging camera in the near-IR wavelength range (based on the Rosetta Osiris instrument). Both units are mounted on a common optical bench and the science objectives are associated, as shown in Table 1, with all the mission phases. The detection of surface ices, organic molecules and minerals, as well as coma gas and dust, requires wavelength coverage from the short-wave visible to the near-IR. Filtering imaging of specific wavelength regions for compound detection, as well as continuum characterization are therefore required. The camera will provide:

- Determination of the global physical parameters of the MBC body, including dimensions, shape, volume, rotational period, axis over time, mean bulk density (together with mass estimation from the navigation and/or radio science experiment)
- Topography characterisation for geological context analysis including surface terrain models
- Characterisation of surface morphology and body geology, including the assessment of the MBC activity trigger scenario through the identification of the impact site and possible surface ices. Surface mineralogy assessment, including the presence of ices, organics and stony material
- Identification of surface activity of dust and gas emissions (locations and time profile)
- Characterisation of the dust and gas dust environment in the MBC coma and tail
- Search for heavier dust grains and boulders in the MBC neighbourhood

By mapping the MBC's diurnal thermal response, the thermal (5 μm to 20 μm) multi-spectral imaging instrument will be able to provide spatially resolved measurements of the MBC's thermal inertia and composition. These measurements can help identify the active region, are vital for planning the targeted observations, and for placing the MBC in a wider geological context. Furthermore, during the close approach, remotely sensed surface thermal maps will prevent any unpredictable spacecraft thermal loads due to local variation in the topography and albedo. Other remote sensing payloads include a deep and shallow radar for internal structural analysis, and a radio science experiment.

In-situ analysis is performed by an impact detector, composition analyser, mass spectrometer, magnetometer and plasma package. The first three are directly applicable to examining the sublimation process and therefore relevant to understanding any ablation analogue event. Based on the ROSINA-RTOF instrument [Balsiger et al, 2007], the mass spectrometer is dedicated to the characterisation of the MBC's gaseous environment. Presented in Table 2, the detector linearly amplifies the signal from incoming particles, providing data on the elemental, molecular and isotopic composition over a wide dynamic range.

Table 2: Scientific Objectives of the Mass Spectrometer

Scientific Objectives	Critical Measurement
Elemental gas abundances	Separate CO from N_2
Volatiles' molecular composition	Measure and separate heavy organic molecules <=250 amu/e
Isotopic composition of volatiles	Separate ^{12}CH and ^{13}C
Development of cometary activity	Measure the composition at different locations along the orbit, joint with CADS
MBC compositional heterogeneity	Mapping of active and inactive regions
Coma chemistry + link surface and innermost coma	Measure neutrals and ion in the mass range of 2-250 amu/e over wide range of pressures

Measurements of momentum, particle fluence and optical cross-section can be achieved through the utilisation of the Grain Impact Analyser Dust Accumulator (GIADA). Based on an upgrade of the GIADA instrument currently flying on Rosetta, it consists of three subsystems including two grain detection systems (GDS) at different wavelengths, an impact sensor and a network of five micro-balance sensors. It can analyse the physical, chemical and dynamic evolution of particles ejected from the active area and examine the spatial and temporal distribution of the dust population [Bussoleti et al, 1999; Colangeli et al, 2007]. The GDS is used to detect the optical transit and cross-section of each particle entering the instrument. It is placed in cascade with an impact sensor, which can determine the velocity and mass of each particle. Detection is limited by the electrical and mechanical noise of the system, and the efficiency of the sensing plate and PZT elements. The micro-balance sensors are used to monitor the cumulative incoming dust deposition rate from the different space directions [Esposito et al, 2002; Colangeli et al, 2007; Palomba et al, 2002]. Table 2 summarizes the instrument's measurement quantity, type and range.

Table 3: GIADA Measurement Parameter. Note: * denotes derived with complementary data

Physical Quantity	Measurement Type		Range
	Direct	Derived	
Speed	X		1-300 m/s
Momentum	X		$6.5\bullet10^{-10}$–$4\bullet10^{-4}$ kg.m/s
Dust Particle Fluence	X		$1.9\bullet10^{-9}$–$2.9\bullet10^{-4}$ g/cm^2
Optical Cross-section	X		Function of the particles optical properties
Mass		X	$2.2\bullet10^{-12}$–$4\bullet10^{-4}$ kg
Flux		X	$6\bullet10^{-12}$ gcm^{-2}s^{-1}
Size		X*	From optical cross-section and dust grain optical properties

The mineralogy of the MBC is determined from a dust composition analyzer. It analyses the refectory composition of the MBC's dust grains based on the analytical method of secondary ion mass spectrometry. In-situ analysis of collected grains determines their elemental and chemical composition. Ejected matter from the inner coma of activity is collected on a material target and is routinely imaged with a microscopic camera. A pulsed primary indium ion beam illuminates the selected grain, releasing secondary ions from the dusty grain surface. A microsphere plate detector counts the secondary ions according to their time-of-flight. The resulting mass spectra reflects the composition of the grain's surface.

Other in-situ instruments include a charged particle spectrometer and a magnetometer. If further iterations of the spacecraft and system design enable more available mass and power, then additional instruments could further enhance the overall scientific return. Additional instruments could include a visible-near-infrared imaging spectrometer, a far UV imaging spectrometer, a sub-mm spectral imager, a subsurface science package, a surface package (a simple lander, for example MASCOT on Hayabusa 2), polarimeter and a volatile in-situ thermogravimetry analyzer.

APPLIED TO PLANETARY DEFENSE

The science and mission activities of the Castalia spacecraft can also be considered as an analogue demonstration of planetary defense activities. Modelling of cometary sublimation uses similar assumptions for understanding the physical and chemical process of surface ablation. The formation of the ejecta plume(s) is comparable to the rocket exhaust in standard methods of rocket propulsion. Gas expands from a reservoir, through a nozzle and into the vacuum of space [Kahle et al 2006; Komle 1990; Gibbings 2014].

Surface ablation itself has been shown to be theoretically and experimentally a promising space-based asteroid deflection technique [Gibbings 2014 & 2013, Vasile et al 2013, Sanchez et al 2009]. Surface ablation is achieved by irradiating the asteroid with a light source. This can either be collected and focused solar radiation via a solar concentrator [Melosh and Nemchinov, 1993; Melosh et al., 1994; Maddock et al., 2009, 2007] or with a laser light source [Vasile et al., 2009]. The absorbed heat sublimates the exposed surface, transforming the illuminated material directly from a solid to a gas. The ablated material then forms into a plume of ejecta. This acts against the asteroid, providing a controllable low-thrust deflection. The resulting thrust can be used to push an asteroid away from an otherwise Earth-threatening trajectory.

Depending on the exact configuration, a controllable deflection event can be achieved with a relatively low spacecraft mass into space and short warning time. Previous proposals have suggested the use of either a GWatt ground-based laser system, a MWatt space-based laser powered by a nuclear reactor or a swarm of spacecraft each equipped with an identical KWatt solar-pumped laser. In the latter, overlapping laser beams on a single spot can be used to increase the delivered surface power density. A swam, as an alternative to a single spacecraft, provides a much lighter and far more adaptable solution. It can be used to increase the flexibility, scalability and overall redundancy of the deflection mission. More spacecraft can be added or removed from the existing configuration, eliminating the need to design and develop new spacecraft. The risk of single point failure is also decreased. A highly redundant mission scenario is preferable as it accounts for large observational uncertainties in the asteroid's material and structural composition, and in the mission design parameters [Zuaini et al., 2012].

Results from the selected remote sensing and in-situ instruments are directly applicable to measuring this event and the effects of the sublimation/ablation process. Data gain can address outstanding areas of enquiry, including [Gibbings, 2014]:

- Measuring the in-situ mass flow rate of the ejecta time and how it evolves over time with varying illumination conditions. Suitable instruments: visible and near IR camera, dust detector, dust composition analyzer
- Measuring the temperature profile of the ejecta plume and the sublimated target. Suitable instruments: thermal IR imager, visible and near IR camera,
- Measuring the initial expansion, distribution and velocity of the ejecta plume. Suitable instruments: visible and near IR camera, dust detector, dust composition analyzer, (mass and charged particle spectrometer).
- Measuring the temperature-dependent effects of any ejecta deposition. Suitable instrument: impact sensor
- Understanding the ablation response of more realistic and representative shape models

The potential for a deflection-induced action can be assessed by either measuring the integral of acceleration imparted onto the object or through the variation in the target’s orbital position and velocity [Vasile et al 2013a]. Variation would be in respect to the nominal orbit before the on-set of any activity. These techniques would provide additional redundancy in the event that the instantaneous mass flow and $F_{sub}(t)$ are both small. For inducing a deflection action it is important to understand the difference between the achievable variation of position and velocity with respect to the normal orbit of the asteroid. It is a real quality of interest in an actual deflection mission, but it is strongly affect by the thrust direction, the starting point of the deflection action and the characteristics of the asteroid.

Furthermore, the impact sensor, as provided on the GIADA instrument, will provide essential information on the momentum and rate of deposition of the impinging sublimated material from different directions. Within the ablation volume, a thin film of deposited material is assumed to form on any exposed surface. The ablated ejecta will immediately re-condense and stick. Influencing factors include the height, density, absorptivity and growth rate of the deposited material. Laboratory experiments have examined this affect further with the ablation of olivine samples with a 90 W continuous wave laser [Gibbings, 2014, 2013]. It demonstrates inconsistencies, amongst others, with the expected levels of contamination. The experimentally determined absorptivity of the deposited ejecta was two orders of magnitude lower than expected. There was no immediate saturation of the exposed surface, nor the formation of a permanently attached substrate. The ejecta was instead loosely bound to the underlying surface. The initial ablation model was found to be overly conservative in an unexpectedly benign environment. However, further work is required to assess the ablation/sublimation response over a full range of samples and illumination conditions. Asteroids exist over a diverse range of compositions, rotations, geometries and surface features. The ablation model needs to be completely modelled and the material interaction thoroughly understood. The latter is an aspect that is unlikely to be known in detail before any mission begins.

Understanding the ejecta-induced contamination effects is a critical factor in spacecraft design, especially in the thermal equilibrium temperature of thermal radiators and ability of the solar arrays as a power generating mechanism. The latter is critical during any close proximity operations. The continual accumulation of the ablated ejecta will ultimately affect the behavior of any exposed surface. For an optical surface located within the ablation volume it will decrease the transmittance and increase the absorbance of the affected surface. More of the incoming radiation will be absorbed, but will be unable to penetrate to the surface below [Dursch et al., 1995]. Reported in [McMullin et al, 2002, Defise et al 1997] the Solar Extreme UV monitor and the EUV imageing telescope, both on board the Solar and Heliosphere Observatory suffered the continual degradation in performance. Contamination can also alter the thermal emittance of any surface or structure. The energy absorbed into the ejecta layer will diffuse throughout and be conducted into the underlying surface. It can increase the thermal equilibrium temperature of any affected unit, and more importantly lead to critical components overheating [Hamberg and Tomlinson, 1971; Tribble, 2000].

Optical contamination causes an increase in the occurrence of background noise [Bousequet et al 1981; Tribble 2000]. Ejected particles captured within any instrument's field-of-view or line-of-sight will obscure, scatter and reflect light. It will reduce the performance of each instrument [Rantanen & Gordon 1996; Dursch et al 1999]. Observations in the far field will become obscured or degraded [Dursch et al., 1995]. Images will exhibit structural background and bright streaks will be caused by the transit of the ejected particles [Dursch et al., 1995]. This will also degrade the ability of the sensor to perform any of its acquisition, detection, imaging and track correction functions [Dursch et al., 1995]. It can result in inaccurate imaging and unreliable detection. Optical payloads are often the most contamination-sensitive surfaces. They frequently govern the contamination-control process of the entire spacecraft and define the lifetime of the mission [Tribble, 2000]. Several missions, including Stardust, Cassini-Huygens, Chandra X-ray Observations and others have experienced unexpected levels of deterioration of their camera systems. System performance depends on the wavelength of the spectral band and the density of the ejecta layer [Dursch et al., 1995]. A suitably large margin of subsystem safety should always be accounted for within the mission design and development process. The success of any mission may depend on understanding the tolerance of the spacecraft and its subsystem design. It will affect the design, material selection and operational margin of any given surface or structure.

CONCLUDING THOUGHTS

Castalia demonstrates how a mission based primarily on science objectives can also be used to increase European competiveness in planetary defense. The mission itself has a large scientific and technology return, serving several synergic communities. By reconstructing the scientific data, the ablation and sublimation models can be validated in a relevant (space) environment. Data can be further complemented with a series of laboratory-based testing experiments and ground-based demonstrations for both the ablation and contamination models [Gibbings. 2014]. It will serve to increase the current technology readiness level (TRL) of an ablation induced deflection event, and the understanding of the near-asteroid space environment.

These additional, opportunistic achievements can be achieved with a mission that utilizes a high TRL and development scheme. Limited technological development is required as the majority of the (sub-)systems have a TRL of 5 or higher. Outstanding areas include the availably of Xenon tanks and Ka-band TWTAs in Europe, and the autonomous spacecraft operations needed to hover at close proximity to the target. Heritage however can be taken from the proximity operations proposed in the Marco Polo and Marco Polo-R missions, and the ground control operations of Rosetta. Following the success of Rosetta, a mission to an MBC would be the natural next step in cometary physics, planetary science and defense. To date, only NASA's Deep Impact mission has delivered a kinetic impactor in the form of a 355 kg spacecraft into the nucleus of a 6 km diameter comet, 9P/Temple 1. The mission however did not yield a measurable deflection event. With their naturally occurring sublimation points, MBCs could provide the demonstration of the chemical and physical properties of ablation based deflection technologies. This can be achieved without the inclusion and qualification of a space-based laser system or large solar concentrators. The capabilities and technologies to deflect an asteroid's trajectory have never been demonstrated in space. Uncertainties exist in the dynamics of asteroids and their largely unknown physical (sub)surface properties. These issues could be addressed with the implementation of the Castalia mission.

ABBREVIATIONS

ESA	European Space Agency
GDS	Grain Detection System
GIADA	Grain Impact Analyser Dust Accumulator
IMU	Inertial measurement unit
IR	Infrared
LIDAR	Laser Illuminated Detection And Ranging
MBC	Main Belt Comet
PZT	Piezoelectric Transducers
PDR	Preliminary Design Review
TRL	Technology Readiness Level
TWTA	Travelling Wave Tube Amplifiers
UV	Ultraviolet

ACKNOWLEDGEMENTS

Castalia was proposed by an international team of engineers and scientist. The mission and spacecraft design was a result of a comprehensive concurrent engineering study. Members of the core team who proposed the mission as a suitable M-class candidate include: Geraint Jones, Kathrin Altwegg, Mark Bentley, Ivano Bertini, Andre Bieler, Hermann Boehnhardt, Neil Bowles, Andy Braukhane, Maria Teresa Capria, Young-Jun Choi, Valérie Ciarletti , Andrew J. Coates, Vincenzo Della, Bjorn Davidsson, Cecile Engrand, Alan Fitzsimmons, Alison Gibbings, Henning Haack, Olivier Hainaut, Pedro J. Gutiérrez, Marcus Hallmann, Alain Herique , Martin Hilchenbach, Maren Homeister, Henry Hsieh, Emmanuel Jehin, Wlodek Kofman, Luisa M. Lara, Javier Licandro, Stephen C. Lowry, Ulysse Marboeuf, Francesco Marzari, Karen Meech, Fernando Moreno, Andrew Morse, Karri Muinonen, Martin Paetzold, Antti Penttilä, Dirk Plettemeier, Dina Prialnik, Alessandra Rotundi, Alan Smith, Colin Snodgrass, Ian Thomas, Kleomenis Tsiganis and Mario Trieloff

REFERENCES

H Balsiger, et al. Rosina Rosetta Orbiter Spectrometer for Ion and Neutral Analysis, Sp. Sci. Rev.128, 745-801, 2007

W.F Bottke, M.C Nolan, R Greenberg, R.A Kolvoord, Velocity distributions among colliding asteroids, Icarus 107, 255, 1994

P Bousequet, F Flory, and F Roche. Scattering from multilayer thin films theory and experiment. Optical Society of America, 71:1115-1123, 1981

E Bussoletti, L Colangeli, J.J Lopez-Moreno, E Epifani, and V Mennella. The giada experiment for the rosetta mission to comet 46p/wirtanen: Design and performance. Advances in Space Research, 24(9):1139-1148, 1999.

M.T Capria, S Marchi, M.C de Sanctis, A Coradini, E Ammannito, The activity of main belt comets, A&A 537, A71, 2012

L Colangeli, J.J Lopez-Moreno, P Palumbo, J Rodriguwz, E Bussoletti, V Della-Corte,F Esposito, M Herranz, J.M Jeronimo, A Lopez-Jimenez, M Epofani, R Morales, E Palomba, and A Rotundi. Giada: The grain impact analyser and dust accumulatorfor the Rosetta space mission. Advances in Space Research, 39, 446-450, 2007.

J.M Defise, F Clette, J.D. Moses, J-F.E. Hochedez, In-orbit diagnostics of EIT EUV CCD radiation-induced aging, Proc. SPIE, 3114, 598–607, 1997

H Dursch, G Bohnhoff-Hlavacek, D Blue, and P Hansen. Analysis of systems hardware flown on Idef: New findings and comparison to other retrieved spacecraft hardware. Spacecraft Design, Testing and Performance, 1995

ESA, Cosmic Vision M4 Call – Technical Annex, SRE-F-2014.035/, 2014

F Esposito, L Colangeli, D Corte, and P Palumbo. Physical aspects of an impact sensor for the detection of cometary dust momentum onboard the Rosetta space mission. Advances in Space Research, 29(8):1159-163, 2002.

A Gibbings, Laser Ablation for the Deflection, Exploration and Exploitation of Near Earth Asteroids, PhD Thesis, University of Glasgow, 2014

A Gibbings, M Vasile, J-M Hopkins, D Burns, I Watson, Experimental Characterization of the Thrust Induced by Laser Ablation onto an Asteroid, Planetary Defense Conference: Gathering for Impact, Session 4: Mitigation Techniques and Missions, IAA-PDC13-04-22, Flagstaff, USA, 2013

A Gibbings, M Vasile, I Watson, J-M Hopkins, Experimental Analysis of Laser Ablated Plume for Asteroid Deection and Exploitation, Acta Astronautica, 90(1):85-97, 2013

O Hamberg and F.D Tomlinson. Sensitivity of thermal surface solar absorptance of particulate contamination. AIAA Paper 71-473 6th Thermo physics Conference, 1971

M. Homeister, A Braukhane, H Boehnhardt, CE Study Team, Science Team, Castalia – A Main Belt Comet Mission, 65th International Astronautical Congress, Toronto, Canada, 2014

H.H Hsieh, The Hawaii Trails Project: Comet Hunting in the Main Asteroid Belt, Astronomy and Astrophysics, 505, 1297, 2009

D Jewitt, The Active Asteroids, The Astronomical Journal, 143(3), 66, DOI: 10.1088/0004-6256/143/3/66, 2012

G.H Jones, Castalia Core Team Members, Castalia – A Mission to a Main Belt Comet, Submission ESA in response to its M4 Call for a Medium-class Mission, 2015

R Kahle, E Kuhrt, G Hahn, and J Knollenberg. Physical Limits of Solar collectors in deflecting earth-threatening asteroids. Aerospace Science and Technology, 10:256{263, 2006

N.I Komle. Jet and shell structure in the cometary coma: modeling and observations. In J.W Mason, editor, Comet Halley: Investigations, Results, Interpretations, pages 232-243. Chichester Ellis Horwood, 1990

C Maddock, J.P. Sanchez-Cuartielles, M Vasile, G Radice. Comparison of single and multi-spacecraft configurations for NEO deflection by solar sublimation. In New Trends in Astrodynamics and Applications III, pg 303-316. American Institute of Physics, 2007

C.M Maddock, M Vasile, C McInnes. Design of a multi-spacecraft swarm for the deflection of Apophis by solar sublimation. In Planetary Deference Conference, pg 1-5. AIAA, 2009.

D.R McMullin, D.L Judge, M Hilchenbach, F Ipavich, P Bochsler,P. Wurz, A. Bürgi, W.T Thompson, J.S Newmark, In-flight Comparisons of solar EUV irradiance measurements provided by the CELIAS/SEM on SOHO, in Radiometric Calibration of SOHO, ISSI Sci. Rep. SR-02, 135–144, Int. Space Sci, 2002

H.J Melosh. I.V Nemchinov. Solar asteroid diversion. Nature, 336:21-22, 1993

H.J Melosh, I.V Nemchinov, Y.I Zetzer. Non-nuclear strategies for deflecting cometsand asteroids. In T Gehrels, editor, Hazards due to Comets and Asteroids, pg 1111-1132, University of Arizona Press, 1994.

E Palomba, L Colangeli, P Palumbo, A Rotundi, J.M Perrin, and E Bussoletti. Performance of mico-balances for dust ux measurement. Advances in Space Research, 29(8):1155-1158, 2002.

R Rantanen and T Gordon. On-orbit transport of molecular & particulate contaminants. In Conference Proceeding of SPIE 2864, pages 115-126, 1996.

J.P Sanchez, C Colombo, M Vasile, and G Radice. Multicriteria comparison among several mitigation strategies for dangerous near earth objects. Guidance, Control and Dynamics, 23(1):121-142, 2009

A.C. Tribble Fundamentals of Contamination Control, SPIE Press, Washington, USA 2000.

M Vasile, C Maddock, and L Summerer, Conceptual design of a multi-mirror system for asteroid deflection. In 7th International Symposium on Space Technology and Science, pg 1-5, Sukuba, Japan, 2009

M Vasile, M Vertisano, A Gibbings, D Yarnoz, J-P Sanchez, J-M Hopkins, D Burns, C McInnes, C Colombo, J Branco, A Wayman, S Eckersley, Light-Touch2:A Laser-Based Solution for the Defection, Manipulation and Exploitation of Small Asteroids, Planetary Defense Conference: Gathering for Impact, Session 4: Mitigation Techniques and Missions, IAA-PDC13-04-22, Flagstaff , USA, 2013

M Vasile, A Gibbings, V Massimo, J-P Sanchez, D.G Yarnoz, S Eckersley, A Wayman, J Branco, D Burns, J-M Hopkins, C Colombo, and C McInnes. Light touch2: Effective solutions to asteroid manipulation. SYSNova Challenge Analysis Final Report, 1:1-164, 2013a

F Zuaini, M Vasile, A Gibbings. Evidence-based robust design of deflection actions for near earth objects. Celestial Mechanics and Dynamical Astronomy, 114 (1):107-136, 2012