Castalia – A Planetary Science Mission to a Main Belt Comet

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Figure 1: The cometary appearance of MBC 133P/Elst-Pizarro

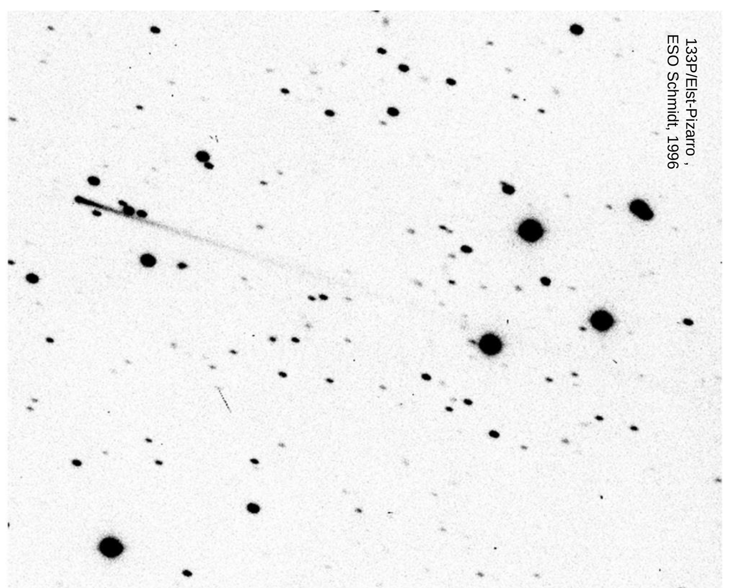


Table 1: Main Belt Comets and other Objects with Activity in the Asteroid Belt

	Discovered	a	e	i	q	Q	T_J	P	r	Last active	Comet?
133P/(7968) Elst-Pizarro	07/1996	3.156	0.165	1.386°	2.636	3.677	3.184	5.6	1.9	07-09/2007	repeats
238P/Read	10/2005	3.165	0.253	1.267°	2.365	3.965	3.153	5.6	0.4	09-12/2010	repeats
176P/(118401) LINEAR	11/2005	3.196	0.192	0.238°	2.581	3.811	3.166	5.7	2.0	11-12/2005	Did not repeat
P/2008 R1 (Garradd)	09/2008	2.726	0.342	15.903°	1.793	3.660	3.217	4.5	0.2	07-09/2007	2013 return
P/2010 R2 (La Sagra)	09/2010	3.099	0.154	21.395°	2.623	3.576	3.099	5.5	0.7	08/2010-02/2011	Comet appearance
300163 (2006 VW_{139})	11/2011	3.052	0.201	3.239°	2.438	3.665	3.203	5.3	1.7	08/2011-01/2012	Comet appearance
P/2010 A2 (LINEAR)	01/2010	2.291	0.124	5.255°	2.006	2.576	3.583	3.5	0.06	03/2009*	Impact?
(596) Scheila	12/2010	2.927	0.165	14.662°	2.443	3.410	3.209	5.0	57	11/2010	Impact
P/2012 F5 (Gibbs)	03/2012	3.00	0.04	9.74	2.88	3.12	3.23	5.2	0.2*	07/2011*	Impact?
P/2012 T1 (Pan-STARRS)	10/2012	3.15	0.24	11.06	2.41	3.90	3.14	5.6	?	11/2012	New!

Figure 2: Orbital elements of 133P/Elst-Pizarro and 238P/Read

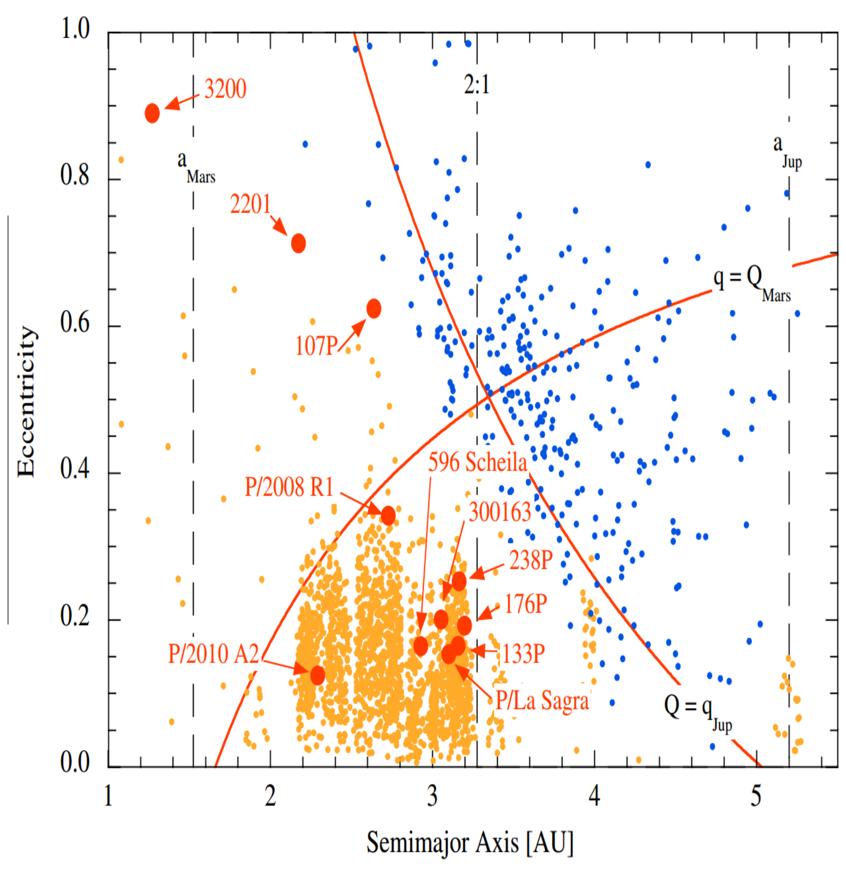


Table 2: Strawman payload of the Castalia mission

No	Payload Name	Type
1	Visible & NIR spectral imager	Remote sensing
2	Radar (deep interior)	
3	Radar (shallow subsurface)	
4	Thermal infrared (IR) imager	
5	Radio science	
6	Dust impact detector	in-situ payload
7	Dust composition analyzer	
8	Neutral/ion mass spectrometer	
9	Magnetometer	
10	Plasma package	

Table 3: The core science mission phases at the MBC in overview

Mission phase	Duration	Main goals
Drift	3 months	Coarse characteriization and approach
100 km orbits	3 months	Global shape Active region(s)
20 km orbits	6 months	Deep Interior and subsurface layers Hi-resolution shape model and mineralogy Activity Temperature maps Gravitiy field
5 km hovering phases	100 h	Activity Gas and dust properties and compostion Remnant magnetism and in-situ plasma activity

Figure 3: Extraterrestrial origin of water: Artist impression of the early hot Earth without water (left), a later cooled-down planet with liquid water (right) and the reality of a cometary impact on Jupiter in 1994 (middle)

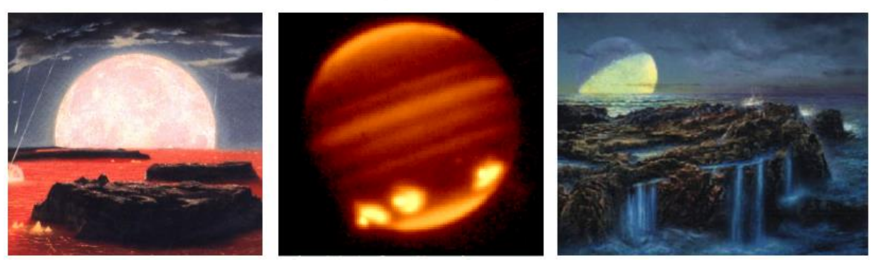


Figure 4: Example transfer orbit to MBC 133P/Elst-Pizarro

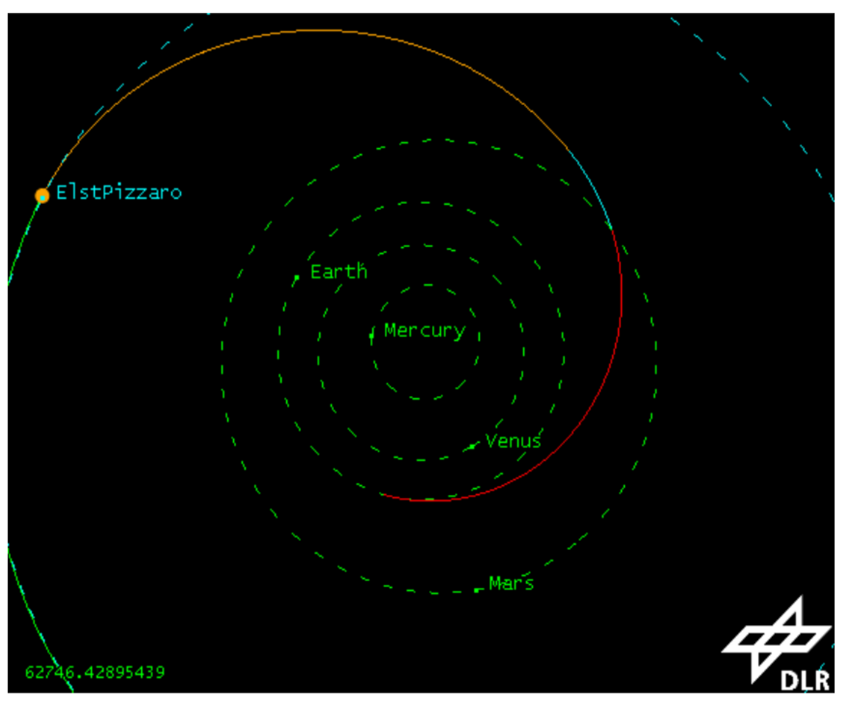
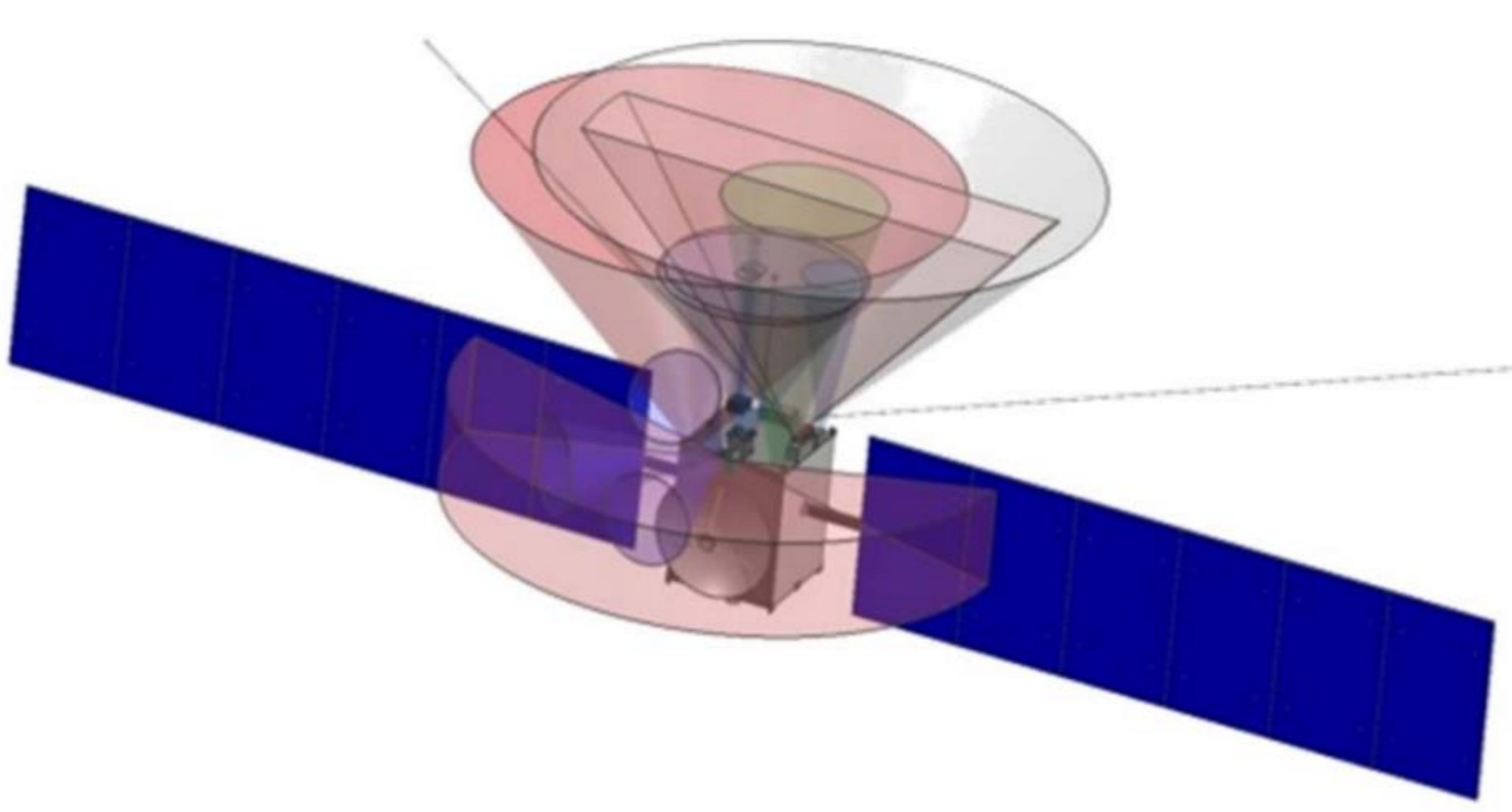


Figure 5: Global view of the spacecraft for the Castalia mission (including field of views of the scientific instruments)



Abstract: **Main Belt Comets (MBCs) are a newly found population in the main asteroid belt. A spacecraft mission to MBCs can provide key insights into the formation and evolution of the planetary system and the early evolution of Earth. The scientific key questions of the mission, its instrumentation and mission profile is studied with the goal to prepare for future mission calls of international space agencies.**

1. What are Main Belt Comets (MBCs)?

Physical and dynamical properties (Figs. 1, 2 and Table 1): MBCs are minor bodies with asteroid like orbits and an – at least temporary - appearance like comets. They orbit the Sun mainly in the outer part of the main asteroid belt. When active – most likely during several revolutions, they emit micron-size dust, although at low production rate (order 1000 tons/revolution). Sizes (order km) and albedos (< 0.1) are small. The first MBC (133P/Elst-Pizarro) was discovered in 1996, and more than 1000 MBCs are expected in the asteroid belt at a time.

Origin and activity scenarios: The origin of MBCs is still unsolved. The current paradigm sees MBCs as either original or at least early members of the asteroid belt. It is believed that they survived in the belt in a dormant state and that their activity occurred only recently and may not last very long. What drives the activity in MBCs is unknown. Cometary-like sublimation of ices is best compatible with the observed phenomenology and very likely the reason for MBC activity. If so, only water ice is expected to be the major volatile that can survive long enough in a body in the asteroid belt, and only when deeply covered under an insulating surface. Excavation by impact could bring the water ice (closer) to the surface and trigger the start of MBC activity.

The terrestrial link (Fig. 3): The presence of water (ice) in the asteroid belt is very important for the presence of water on Earth. Nowadays, water up to the volume of a 1000 km diameter body exists on Earth. However, the origin of water on Earth is unsolved. A likely scenario is that water did not survive from the formation phase of the planet, but was imported to Earth thereafter. At about 4 billion years ago, liquid water existed (again) on a solid terrestrial surface. Re-import of water could have happened by means of impacts of planetesimals during the clean-up process of the planetary debris disk. The asteroid belt has by far delivered the most impactors to Earth, compared to the outer solar system where the comets reside. Related is the possible import of organics and even biogenic material from extraterrestrial space.

Why a mission to an MBC? A Main Belt Comet mission has the potential to address and solve scientific key questions related with the asteroid belt and the early evolution of the terrestrial planets:
What are the physical properties and constitution of MBCs? How does the activity work? Do they keep a significant amount of water and organics? Where was the snowline when the planetary system formed? Are MBCs a potential source for the terrestrial water and organics on Earth?

2. The Castalia Mission to a Main Belt Comet

Mission goals and objectives: The Castalia mission will explore a member of a new class of small bodies that can provide unique insights into the distribution of volatiles in the early stages of planet formation and the interrelation of water and organics in the asteroid belt with life on Earth.
The science goals of the Castalia mission at an MBC are:

1. Characterize a new Solar System family, the MBCs, by in-situ investigation
2. Understand the physics of activity on MBCs
3. Directly detect water in the asteroid belt
4. Measure D/H ratio to test if MBCs are a viable source for Earth's water
5. Use MBCs as tracers of planetary system formation and evolution

These goals map into to the specific scientific objectives for the Castalia mission as follows:

- Measure global characteristics of the nucleus
- Map surface structure, geology and mineralogy, including hydrated/organic minerals and search for ices
- Determine (or constrain) the subsurface and internal structure
- Confirm impact activation hypothesis, by identification of impact site
- Determine minor volatile species' elemental and molecular abundances or sensitive upper limits
- Determine the dust's elemental and molecular composition, structure, and size distribution and compare it to comets and asteroids
- Determine the D/H ratio, and isotopic composition of the MBC
- Characterize the diurnal and orbital activity cycle
- Search for a primordial magnetic field in a small solar system body
- Characterize the plasma environment of an weakly out-gassing object and its solar wind interaction.

Scientific payload: The strawman instrument payload is defined as those necessary to characterize a MBC, locate its active area(s), identify the activation process and the activity driver and sense possible links to the terrestrial planet formation and evolution through measurements of isotopic ratios of water and organics. It is summarized in Table 2.

Mission type and mission target: The anticipated science goals are best and easiest achieved through an orbiting mission to a single MBC. Several other mission types are considered to also accomplish the goals, but at higher complexity and costs. Fly-by missions at one or more targets are questionable to reach the Castalia science goals. The best target, since best studied for its MBC nature, is 133P/Elst-Pizarro with 238P/Read considered as best known back-up candidate (Figure 2).

Science mission at the MBC: For the achievement of the science goals and objectives four core mission phases at the MBC are defined. These phases focus on science operations in different distant ranges around the target: the approach phase beyond 1000km for a coarse characterization, the orbiting phase at about 100km for measurements at global scale and medium resolution, the orbiting phase at about 20km for the global characterization of the nucleus and its interior and a close approach phase with about 5km distance to the MBC for the in-situ analysis of its activity. Obviously, the latter has to be performed during the active period of the target. The core science mission phases can be complemented by an excursion into the plasma tail region some 10000km away from the nucleus and/or a soft landing with the orbiter spacecraft at the surface. Information on the scientific measurements during the 4 phases is compiled in Table 3.

Mission analysis: The Castalia spacecraft is launched in 2024 by a Soyuz-Fregat-type launcher. Electric propulsion is used for the cruise phase to the target 133P/Elst-Pizarro. The cruise phase is about 5 years long and may involve a gravity assist by Mars. Fly-bys at other asteroids in the main belt may be possible during cruise, but are not yet analyzed. Upon arrival at the target the science mission as described above will start with the exploration of the MBC during a year of up to a year before activity onset followed by the science investigations during the active phase which could easily last 1 year or longer. Plasma tail excursions and/or soft landing of the orbiter towards the end of the mission appear feasible, although not analyzed in detail. Several launch windows exist for 133P/Elst-Pizarro as well as the back-up target 238P/Read. An example for the transfer orbit to 133P/Elst-Pizarro is given in Figure 4.

Mission spacecraft: The spacecraft bus was engineered to contain the electric propulsion system, the attitude and orbit control system, the communication and data handling environment, the power subsystem with larger solar arrays, the thermal control system, the bus structure and harness. The payload instruments, in total about 70kg, were integrated in and on the spacecraft bus according to the requirements for the respective observations and operations. Figure 5 provides a global view of the spacecraft for the Castalia mission. The total 'dry mass' amounts to about 1400kg (including margin) resulting in a total 'wet mass' below tha maximum launch capacity of the Soyuz-Fregat launcher.

Mission challenges: The scientific and engineering analysis for the Castalia mission has revealed challenges for the spacecraft operations, namely the transfer operations towards the asteroid belt with the long operation periods of the electric propulsion system and high demands to the power subsystem, the autonomous in-situ hovering operation of the spacecraft at a few km above the MBC surface, the radar measurements of the body interior and the gas and dust collection during the active phase of the MBC.

3. Conclusion

The Castalia mission will illuminate the nature of MBCs and their role in the planetary formation as well as for the life on Earth. Main target is 133P/Elst-Pizarro with 238P/Read as a back-up. The mission can be launched around middle of the next decade and will require about 6-7 years for completion. Spacecraft and instrument technology is available or at a suitable level of readiness for successful implementation in the Castalia mission. The spacecraft envelope and financial budget of the Castalia mission is at the level of a typical ESA M-class mission.

Acknowledgements

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