Satellite Dynamics and Space Missions: Theory and Applications of Celestial Mechanics

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Space missions for minor-body science

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PLAN of LECTURES

1. **Self presentation and method**
2. **Mission design and implementation: a difficult process**
3. **Case A: ROSETTA, cometary mission**
4. **Case B: MORO, a proposed lunar mission**
5. **Why so many asteroid missions?**
6. **Case C: DON QUIXOTE, a proposed deflection experiment**
7. **Asteroid families, proper elements, and asteroid ground truth**
8. **Case D: DAWN, rendez-vous asteroids mission**
9. **Next asteroid missions: LUCY, PSYCHE**

1.1 Self presentation

Old persons have plenty of memories. The challenge is to select the important ones, not just for the old, but for the next generations. The challenge for the young listeners is to be receptive, but critical: do not do as we did in our times, but learn lessons to apply in innovative ways to the new experiences.

In the early sixties I was a teenager with some very passionate interests, including exploration of space: these were the times of the first human spaceflights, and of the race for the moon. I also liked computers, not accessible to me, but I did study my first programming language, FORTRAN.

In 1976 I was aged 28 and already with a tenured position (Assistant of Mathematical Analysis) in the University of Pisa. However, my research career in pure Mathematics was going nowhere.

Then, following the advice of A. Nobili and P. Farinella, I attended the lectures by Giuseppe (Bepi) Colombo at SNS. Colombo was not lecturing in the ordinary sense: he would arrive at the airport, directly from USA, and in the car while we were bringing him to SNS he would start showing us documents (often marked "confidential") containing new results from NASA observations and space missions, and soliciting us to study the interaction of abstract celestial mechanics with solar system dynamics and spaceflight.

1.2 Mathematics has to cope with reality

The challenge in Colombo's proposed research was not just knowing mathematics, but finding ways to apply it to the scientific problems arising in the exploration of the solar system, and even in the technological problems of space-faring.

Some mathematics can indeed be applicable: celestial mechanics is the best example because of the extreme accuracy of the predictions, resulting from simple models, such as the N-body problem (maybe with some extra tricks).

Once we started confronting with the demands from the space missions, we found this was much less easy than expected. As reality entered in the contents of our research, it was not possible to allow in just the portion we liked. E.g., it is not enough to study the orbit of a solar system body, it was also necessary to find how to measure it, and from where, that is to select the orbit of the spacecraft capable of such measures.

Then from the process of **mission analysis**, we ended up discussing how massive the spacecraft has to be, including the fuel needed to get to the needed orbit. Then we got entangled in the decision process to select which missions can fly, taking into account its cost. Once someone loses the innocence of pure research, there is no way back. My friend Paolo Farinella made the opposite choice, never to be personally involved in a real space mission.

1.3 Method: little theory, case studies

As it should be clear from above, this mini-course shall contain a very small dose of theory, which is simply based upon my experience as consultant (mostly for ESA) in the design and selection of space missions to small solar system bodies. I shall explain the process of selection of space missions, at least here in Europe, and some of the structural difficulties in the implementation of what was decided.

I shall mention also NASA, for which I have also worked, but honestly my experience with NASA is limited, and it also occurred later than the golden age of American solar system exploration, to which Colombo participated successfully. This age was (badly) concluded by the Galileo mission to Jupiter.

My method for these lectures shall be mostly based on **case studies**: I shall discuss (a maximum of) 5 space missions to small bodies of the solar system (asteroids, comets, and natural satellites).

Not discussed here other missions I was involved with: Cassini, BepiColombo, GOCE, JUNO, JUICE, because planetary missions are even more complicated.

2.1 Design of a Science Mission

The design of a scientific space mission should always be top-down, starting from the scientific goals. Thus a team of scientists, supported by engineers from ESA and from industry, is formed.

This work starts from the state of the art about a given class of bodies (asteroids, comets, icy satellites, rocky satellites, transneptunians) and by finding which are the most relevant, outstanding questions about them. They can be about the origin, the structure, the collisional history, the composition, the dynamics (of the orbit, of the rotation), and more (examples). The questions have to “scientifically sexy”: an interdisciplinary committee of scientists have to judge which mission is selected.

The next step is to find out if existing instruments, or combination of them, can measure the answers to these questions. If not, which new instrument(s) needs to be developed. For a first visit, a few images, taken from a short distance with a camera, can contain key answers (Io from Voyager, Comet Halley from Giotto). For a second visit (to the same object or class) a deeper investigation is needed, e.g., the interior structure and composition, the rotation state, the collisional history: this requires sophisticated instruments, and a S/C flying low. This requires specific technological competence in the team, and the balance between this and “pure science” can be a problem.

2.3 Confronting with limited resources

A new space mission is studied in a sequence of stages, called (in ESA) feasibility, phase A, and phase B studies. Since the first step it is necessary to propose not only the instruments, but all the S/C subsystems with the necessary capabilities.

For examples: the injection of the S/C in the required orbit imposes a budget of velocity changes, corresponding to a fuel budget (given the performance of the propulsion system) and to the total mass. The mass must include structure, propulsion and fuel, electric power (and possibly heating), attitude control, communications, the payload of instruments, and all the wiring between these subsystems.

At the very least four budgets have to be computed, with safety margins: fuel for propulsion and maneuvers, electrical power (and batteries), data transmission (and on board data storage), thermal state. A large science space mission is one of the most complex systems ever assembled, requiring not one, but many innovative technologies. Often this is not included in the formation of aerospace engineers.

Last but not least, the economic budget needs to be estimated, and this turns out to the most uncertain of the budgets (for all agencies). Is this the most important? Maybe not, although of course space agencies cannot afford to undertake missions sure to exceed, by a large amount, the allocated budget. The truth is, few believe in the cost estimates.

2.4 Winning and loosing

The procedure to select a new space mission is complex and colorful, especially for a science mission. At the end of each study phase, the project is presented to a large assembly of scientists and space professionals (often the venue is a very large hall belonging to UNO in Paris). Each team is given a span of time to present its mission, in a style of presentation which is a strange mix of real science, technological jargon, popular science and public relations. Each presentation is followed by an open debate, which tends to be rich of blows below the belt from the followers of the competing missions.

Who wins? In theory, a mission scientifically appealing, but with a cost within the budget available, and with a reasonable "technological risk". In practice, cost estimates can be fake, the value of a scientific goal is appreciated differently by scientists of different disciplines, the influence of industry and politics cannot be avoided. It is important to learn how to loose, and try again.

As for myself: I started in the 80's with innovative proposals of space missions (to ASI, to ESA) which got nowhere, in the 90's and the first half of the 00's I was involved in ESA studies as part of official science teams. I was in 8 mission study phases, part of competitive mission selections, for 5 different missions, 3 different ESA directorates. Our team won in 7 out of 8 competition. The competition in which our team most deserved to win was the one we lost (MORO).

2.5 The agony of implementation

If you think that once “your mission” has been selected the most difficult phase is over, think again. Due to the complexity of science space missions, and also to the nonsense of ESA budget allocation, a large science space mission takes decades to be implemented. The record is held by BepiColombo, which I designed in 1996-1998 for an expected launch in 2007, arrival to Mercury in 2009. Now it is expected to be launched end of 2018, arrive to Mercury end of 2025.

The reasons are the unreliable cost estimatse, which are handled by spreading the cost on more budget years, and the complexity of the technology, making very easy to do first order mistakes. E.g., after selection of the supplier for the BC bus, it was discovered that the estimate of the launch mass was 600 kg less than the real value. Then the mission was continued (with a larger launcher) without increasing the available power for the ion propulsion, thus making the travel time to Mercury longer than the one of the NASA Messenger mission with chemical propulsion only.

NASA is not less subject than ESA to first order mistakes (Apollo 13, Challenger, Contour, Galileo, ARM); being a national agency they are more subject to political meddling by the President and by Congress. Sometimes, when the politics is supportive, they can implement much faster, so that ESA proposes a mission, by the time they launch it the competing NASA mission is over (Messenger to Mercury 2004–2015).

3.1 The ROSETTA cometary mission: origin

The Rosetta mission history begins in 1985, when ESA Solar System Working Group proposed a comet sample return mission as one of the “cornerstones” of the agency scientific program. A joint ESA-NASA study started at the end of 1985.

In 1986 the perihelion passage of Comet Halley allowed a fleet of S/C, 2 small Japanese, 2 from USSR, and one from ESA, flew by the comet providing data. ESA entry, the probe Giotto, got to < 400 km from the nucleus and provided images which changed our concept of comets forever. NASA was absent, because both a Halley sample return and a fly-by mission were refused by congress.

3.2 The failure of NASA-ESA cooperation

NASA decided to pursue his own comet mission with CRAF (Comet Rendezvous Asteroid Flyby), while ESA and NASA together studied the Rosetta mission, both based on the so called “universal bus” Mariner Mark II (the Cassini bus) to save on the development costs (in S/C manufacturing, most of the cost).

Then in 1992 NASA canceled the CRAF project due to budget cuts (Cassini barely survived, somewhat descoped). Starting from the 80’s, as a consequence of the wrong choices made with the shuttle program, and also because of the 1986 Challenger accident, NASA ended by canceling most robotic exploration missions, leaving a few underfunded and poorly planned, leading to failures. The most prominent was the failure of the main antenna of the Galileo mission to Jupiter.

As a consequence of the decline of NASA leadership, ESA was left alone to work on the Rosetta project, and soon realized that the cost was exceeding the resources from the agency science program. At the same time, the success of Giotto, the cancellation of many NASA exploration missions, and also a string of failures in soviet missions (especially to Mars), was providing ESA with unique examples and opportunities to achieve ’space firsts” before everybody else.

Thus ESA decided to study a descoped Rosetta mission to be performed within the envelope of resources, including cost, previously allocated for a joint mission.

3.3 The descoped ROSETTA

In 1992, ESA nominated an enlarged team for the Rosetta study, to replace some NASA representatives and to provide a fresh insight, for a radical redesign of the mission. I was one of the new members, less experienced than many of the others.

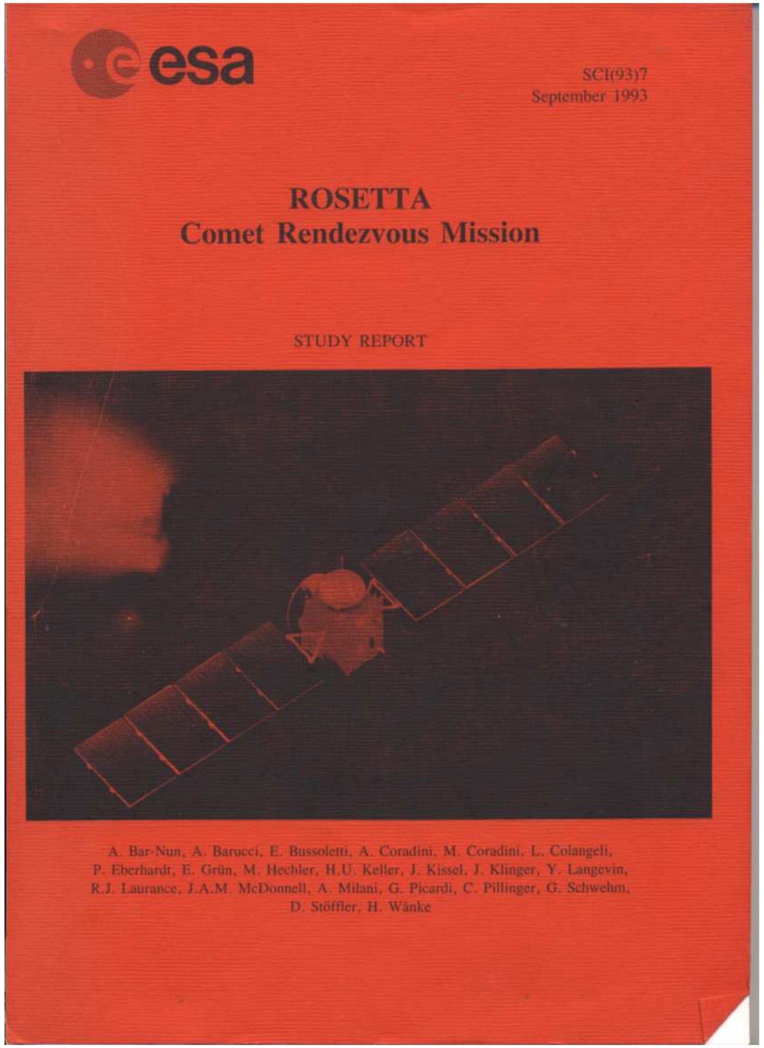
The first approach was to try to propose (and justify scientifically) an asteroid rendez-vous mission, possibly with sample return. I proposed to visit some 'asteroid" which might actually be a dormant comet, like comet Wilson-Harrington recently recovered as asteroid 1979 VA, and a very small sample recovery, allowing a cheap reentry capsule. This because I was representing the scientific community studying asteroid in the team. This would have been feasible, but was not considered scientifically interesting enough (later asteroids shall be more popular).

In the end the science team proposed a rendez-vous with an active comet, preceded by two asteroid fly-by. The comet target was selected as comet 46P/Virtanen, to be reached in 2014 after a launch in 2003. (This looks like CRAF!)

After a long discussion on what was supposed to be the activity of the S/C while orbiting around the comet, we proposed a big complement of remote sensing instruments to be operated from a powerful orbiter, capable of operating quite far from the Sun (but without the nuclear power unit of the NASA missions).

3.3 The final report

The final report of the study team was delivered in September 1993, and the Rosetta mission was approved as proposed, although later in the implementation phase many changes were introduced.



3.4 The lander dilemma

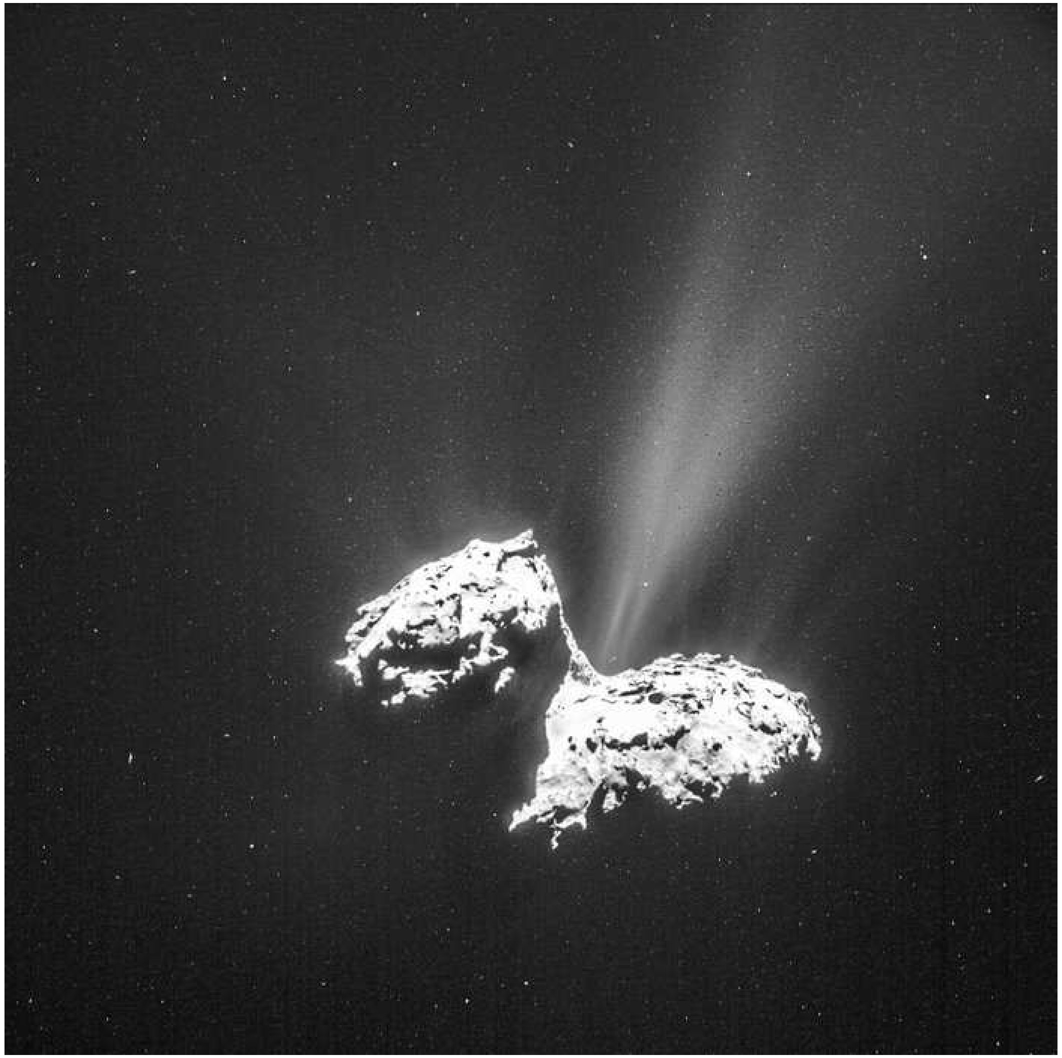
The difficult part of the lander delivery is not the trajectory from the orbiter to the comet (velocity few m/s, low target accuracy). The problem is how to make the lander stick to the comet. The science team considered that a S/C with attitude control and propulsion to push, allowing time for anchoring, would be over budget.

On the other hand, a lander without such control could bounce away from the comet. Even with some damping it would rebound and come to rest several hundred meters from the initial impact point. Moreover, the final attitude could not be guaranteed, thus some capability of “toppling over” would need to be incorporated.

A few weeks before the expected launch of Rosetta, there was an Ariane launch failure, thus Rosetta was delayed more than one year and towards a new target, comet 67P/Churyumov-Gerasimenko, where it arrived in 2014.

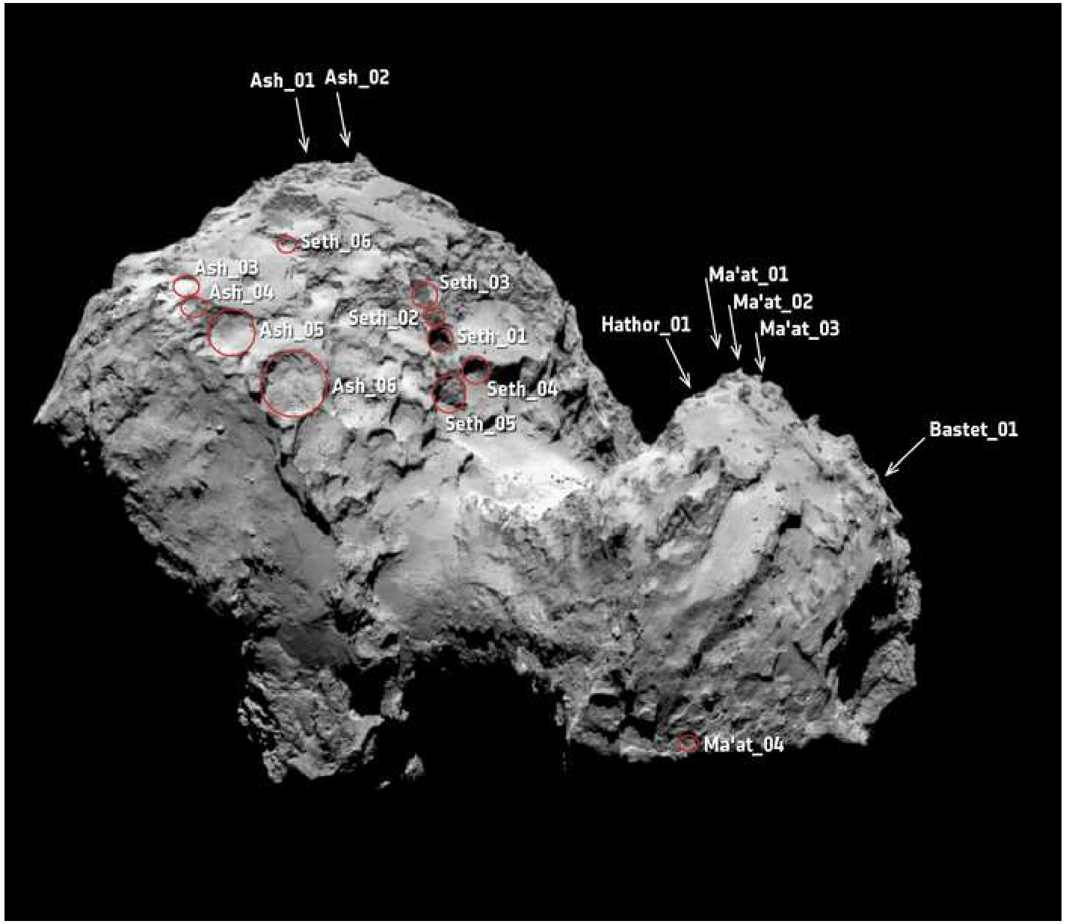
The lander Philae was implemented as a “provided item” from DLR, and had been in storage, first on the ground, then on the main S/C, for more than 12 years.

3.5 Comet from the orbiter 1



What is this image? Navigation mode.

3.6 Comet from the orbiter 2



What is this image? Processed mosaic.

3.7 Orbiter realeases lander

What is this image? Composite.

3.8 Who was right?

Philae hit the comet near the target position, but both the push down motor and the anchoring harpoons failed, thus the lander performed three bounces and ended up many hundred meters away from the target, wedged in a dark crevice, and with a wrong attitude not allowing the use of instruments to collect samples from the comet. Moreover the solar panels were not illuminated, thus Philae ceased to transmit when the batteries were discharged.

ESA tried to deny that Philae was a failure, arguing that it had transmitted some data from some instruments for most of the first planned “science sequence”.

It was later found that the harpoons launch device had not fired at all. This might be due to the too long storage time, the explosive devices not being guaranteed for such a long long time.

During the implementation phase, several other options had been considered for the design of a more capable lander, but discarded because too expensive. Thus the prediction from the Science Team that a reliable lander could not be realized (with the very limited budget available) were fully confirmed.

4.1 The MORO lunar mission: proposal

The proposal MORO was presented, with Coordinator Angioletta Corradini, in 1993 for a selection of a “medium” mission to be launched in 2003. Moon ORbiting Observatory had acronym MORO, which also allude to Shakespeare’s Othello.

This proposal was selected among the 7 for which ESA funded an Assessment Study. A Science Team and an Engineering Team were formed, and the results were presented in Paris on 3-4 May 1994.

Although not previously a specialist of the Moon, I had anyway the possibility of leveraging my experience in satellite geodesy: I proposed that MORO should release a small LUnar Sub Satellite (LUSS) orbiting at some distance (~ 100 km) from the main S/C, to compute the relative range rate by the Doppler effect. This allowed to measure globally the gravity field of the Moon: at that time the gravity anomalies were well known on the near side of the Moon, unknown on the far side (because direct tracking from Earth was impossible).

The version of the mission design presented for the second selection was stronger than the proposal, especially in instrumentation, with a more advanced multi-spectral imaging system, an X-ray spectrometer, and LUSS. The technical challenges of the mission, although ESA had no experience of lunar exploration, appeared reasonable. Indeed, in 1994 MORO was selected for a to a phase A study.

4.2 The Lunar Orbiter coverage problem

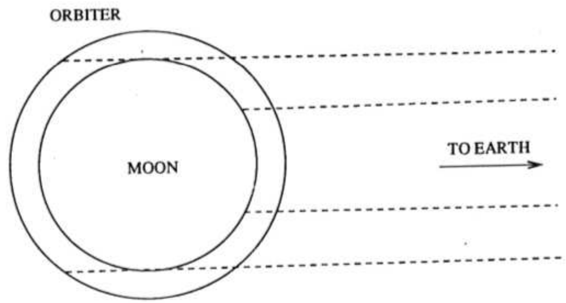


FIG.3 THE OBSERVABLE AREA IS MORE THAN HALF

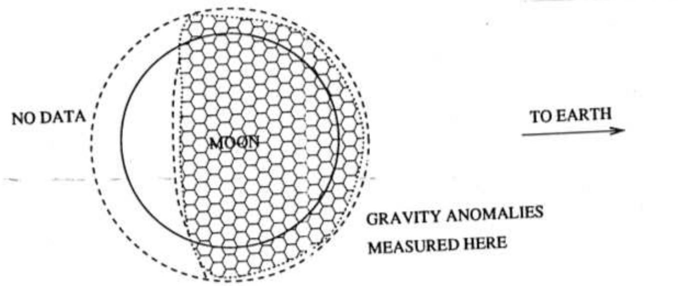


FIG.4 THE HALF BOUNDARY PROBLEM

The Moon always hides the far side from direct view from Earth, thus tracking of a low lunar satellite is possible only when it is flying above 55% of the lunar surface.

If the solution for the lunar gravity field is expressed in spherical harmonics, then they are not a suitable base (othogonal only over the entire surface). In practice, horrendous correlations between harmonic coefficients degrade the solution, which ends up by modelling only the field on the near side.

4.3 The partial boundary problem

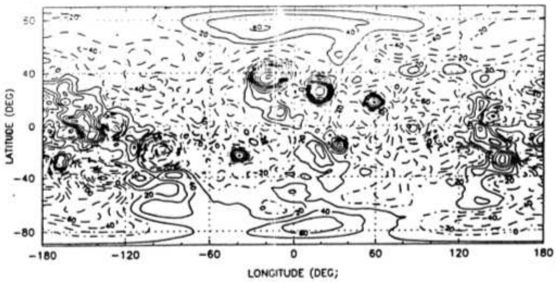


Fig. 4 Radial Acceleration at 100-km for Lun60d

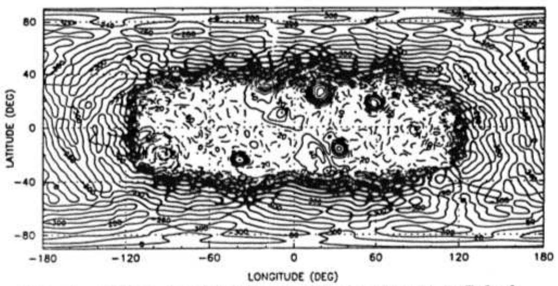


Fig. 5 Radial Acceleration at 100-km without A Priori

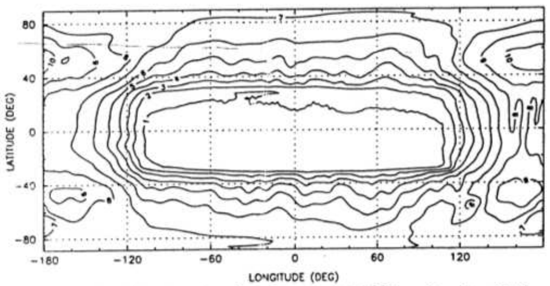
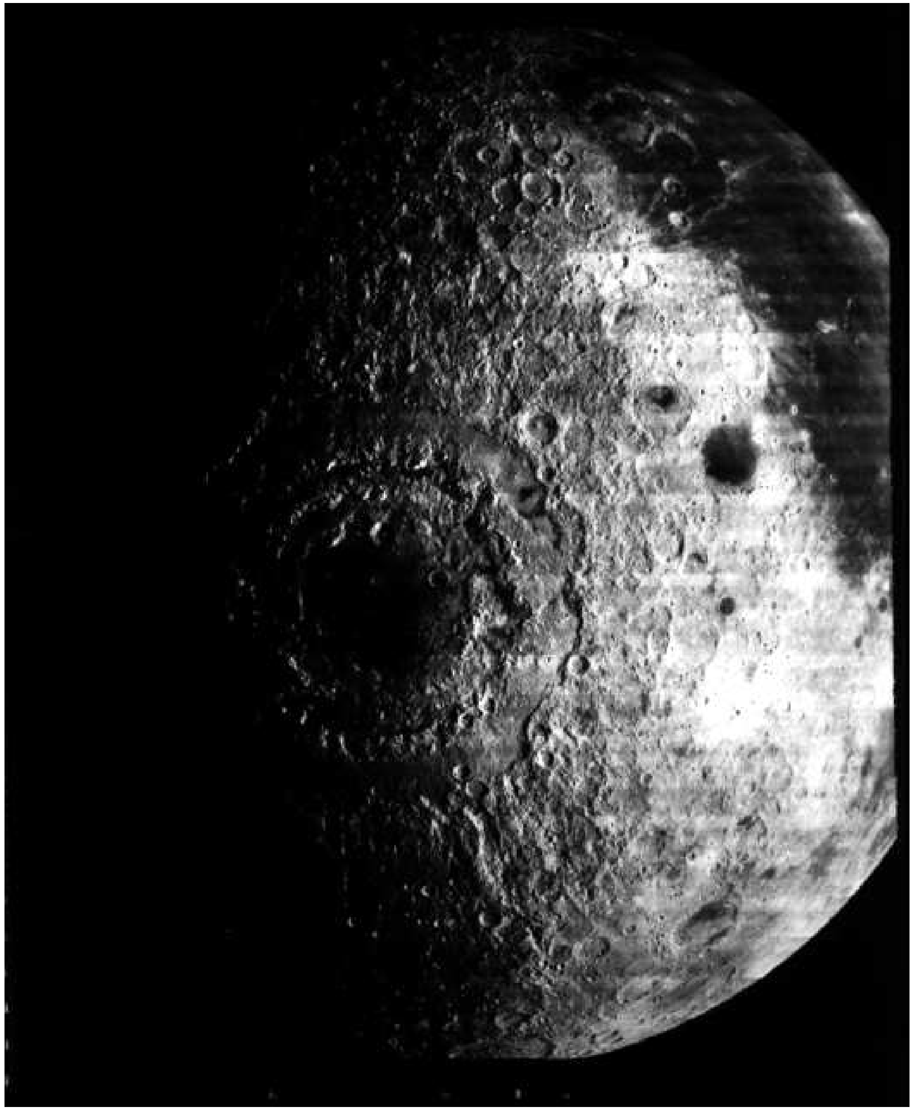


Fig. 6 Radial Acceleration Errors at 100-km for Lun60d

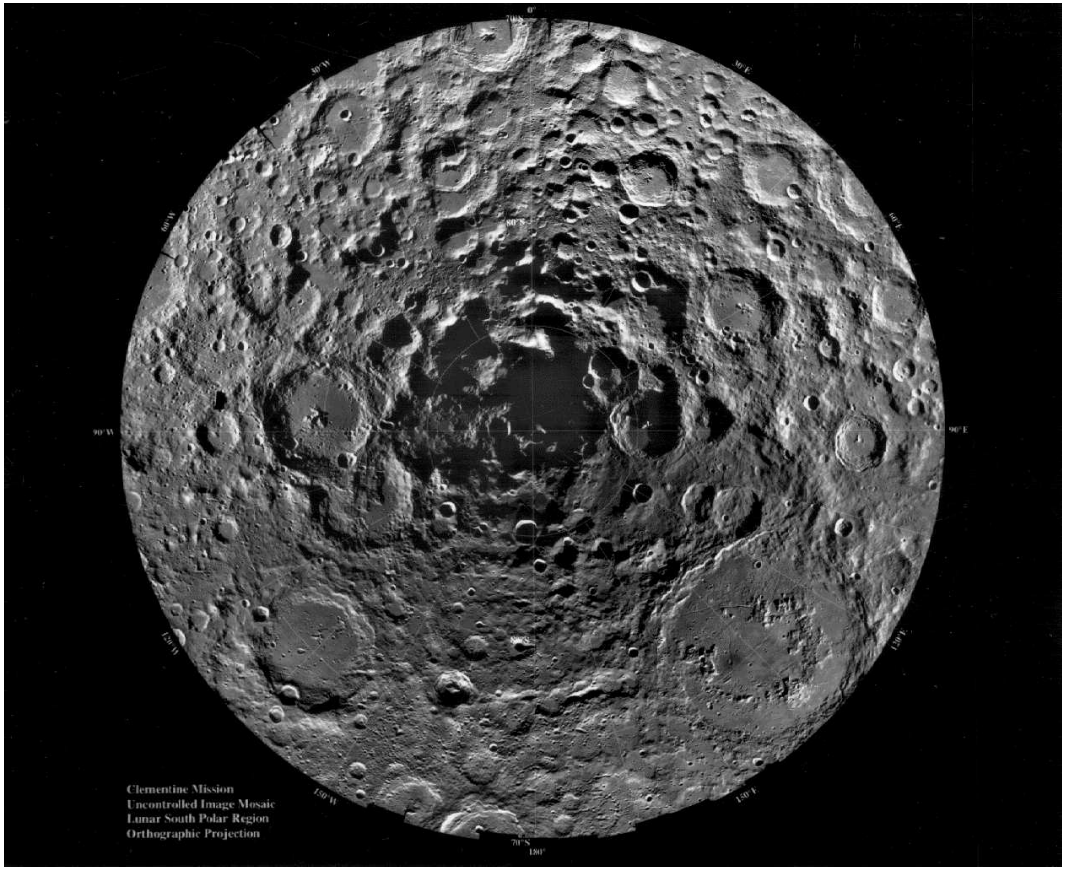
Given that tracking is limited to the near side, the near side gravity anomalies are well determined, the far side ones are essentially undetermined.

4.4 The Apollo legacy



Apollo project: Lunar Orbiter mosaic showing the Orientalis impact basin

4.5 Competition and the next exploration stage



The USA mission Clementine to asteroid (1620) Geographos was motivated by the test of miniaturized instruments. Clementine was launched in 1994, made a stopover at the Moon, then failed (software mistake) during the transfer from the Moon to Geographos, and thus was reclassified as a lunar mission. Anyway it also decreased the novelty of the proposed MORO investigation. Mosaic of Clementine images shows the South Pole crater Aiken (2000 km).

4.6 To the brink of success

In the phase A study of MORO I was more committed than in any other mission. I was the editor of the “red book” (Phase A Study Report), and one of the two scientists (the other was Langevin) giving the talk presenting the mission for the final selection among the 5 candidates. The discussion was rather harsh, but we managed because we had done a really good work.

The selection was, in theory, decided by two committees of scientists: the Solar System Working Group, who was to propose one of the 2 Solar System missions, and they proposed a Mars mission. Then the interdisciplinary Science Advisory Committee proposed a cosmic background mission, later renamed Planck.

The pressure of ESA executive had been strong, because of the synergies with another mission already approved, later called Hershel. These two were launched with a single launcher, in 2009: 6 years late and with a horrendous cost overrun.

In conclusion, this was the mission for which I worked most hard in the study phase. The final selection was the only competition for ESA missions I lost, and the choice turned out to be a deadly mistake for ESA, who accumulated such a delay and deficit that they had to cancel one medium mission. The following large missions Gaia and BepiColombo were delayed by many years.

5.1 Why so many asteroid missions?

In 1992 to propose to ESA an asteroid mission was a lost cause (actually, we proposed an asteroid mission called Piazzi to ASI in 1986). Now the list of S/C visits to asteroids includes:

- flyby to Gaspra and Ida by Galileo (NASA)
- flyby to Mathilda by NEAR (NASA)
- flyby to Lutetia, Steins by Rosetta (ESA)
- flyby to Toutatis by Chang'e-2 (China)
- rendez-vous with Eros by NEAR (NASA)
- rendez-vous to Itokawa by Hayabusa (Japan)
- rendez-vous with Vesta and Ceres by DAWN (NASA)

That is 6 flyby and 4 rendez-vous, not to count failures (Clementine, Contour, Phobos) and two S/C now flying to rendez-vous and sample return (Osiris-REX and Hayabusa 2).

Two things to be explained: first, why the perception by the space agencies of the importance of the asteroids is so much changed and second, why the scientists continue to be interested after having already seen so many asteroids.

5.2 Asteroid are dangerous

Starting in 1991 NASA begun to assess the risk of asteroid impacts upon Earth, and explore the possibility of mitigating such risk with a ground based survey to discover Near Earth Asteroids (NEA).

In 1998 US Congress mandated NASA to discover 90% of the NEA in ten years; NASA set up a system of surveys, with telescopes contributed by observatories and by the Space Command, and making full use of the CCD technology.

This **Spaceguard survey** (name from A. Clark novel) was very soon successful, with the rate of discovery of NEA increased by an order of magnitude.

However, was the fact of discovering a NEA decreasing the impact risk upon Earth? What is the advantage of knowing the name of the asteroid falling upon Earth? The PR disaster of 1997 XF11 in March 1998 showed that the scientific community was not prepared to compute the probability of an asteroid impact, not even within the next 20-30 years.

In 1999 we (Milani, Chesley and Valsecchi) solved the problem of finding **Virtual Impactors**, that is sets of orbits leading to impact (in a given year) but compatible with the observations, and computing the associated Impact Probability.

5.3 Cassandra and the five step plan

Milani and Valsecchi, 2002 and 2003 public talks:

When we discuss in public the asteroid/comet impact risk, we are not listened and disliked. Moderation does not help.

The myth of Cassandra: Apollo's gift of prophecy, curse of disbelief. She predicted the fall of Troy, was hated and imprisoned in a tomb. She was right, but fate could not be changed by humans, thus her announcement only did harm.

To avoid the Cassandra effect we need to prove that, thanks to our research, Troy will be less likely to fall in the next 100 years or so.

A five step plan

1. Detecting many moving objects: NEO Surveys
2. Orbit Determination; Identification
3. Predicting Collisions; Monitoring for impacts; Virtual Impactors
4. Destroying Virtual Impactors by Observation
5. Deflecting a certain Impactor: Know-how and actual Preparation

6.1 The NEOMAP competition

The beginning of dedicated NEO surveys (in USA only) raised much more attention on asteroids, but the Cassandra argument was the winning one: space agency (including ESA) begun to think that all five steps, and especially preparation for deflection, could be part of their mandate.

In 2002 ESA launched a competition NEOMAP for proposing a space mission which needed to be about Near Earth Objects (NEO) and somehow address the impact risk. 20 different mission concepts were proposed. I got a phone call from Miguel Bello' Mora, CEO of Deimos, asking whether I had something to propose, and of course I had to propose step 5, that is an asteroid deflection test.

This mission, named **Don Quijote**, was indeed among the 6 selected for a feasibility study. Note that the competition was not for a science mission, but a mission for a specific *risk mitigation* purpose. Nevertheless, in the interpretation of my group (and of Deimos), Don Quijote had to have a very significant science component, because of the knowledge needed to successfully perform a deflection.

6.2 The Don Quijote proposal

The basic idea of Don Quijote was as follows: a S/C (Sancho) would perform a rendez-vous with the target asteroid, remaining there long enough to study in great detail both the physical properties of the asteroid and its heliocentric orbit. Then Sancho would withdraw to a safe distance, and another S/C (Hidalgo) would arrive on a very different orbit, one with a fast flyby, and impact the target with the goal of transferring as much as possible linear momentum. Then Sancho would come near the asteroid again and observe the crater and any other change, and measure the post impact heliocentric orbit. There are three main difficulties in asteroid deflection with this class of **kinetic impactor** methods:

1. An impact excavates a crater: the ejecta from the crater are launched backward (for an impact near the target center), thus the linear momentum carried away by the ejecta adds to the linear momentum of the impactor L, generating a change in the linear momentum of the asteroid with crater αL, where the *Paolicchi efficiency factor* α is > 1 (unless the impact is grazing) and can indeed substantially increase the orbit deflection. α depends upon the velocity of impact, on the incidence angle on the surface, on the composition of the asteroid near the crater, and on the pre-fracturing of the material, e.g., on the presence of regolith.

6.3 The Don Quijote studies

2. The impactor needs not only to hit the target asteroid, but at a tightly constrained location and time, also because of the need to select a given terrain. Given the high relative velocities (in the range 10 to 15 km/s), the terminal guidance of Hidalgo is not trivial.

3. Before and after the impact, the heliocentric orbit has to be determined, with enough accuracy to measure the orbit change. For reasonable mass impactors (500 kg class) and an asteroid with a diameter of a few hundred meters, the deflections are measured in microns per second. This also implies that non-gravitational perturbations in the asteroid orbit need to be well determined.

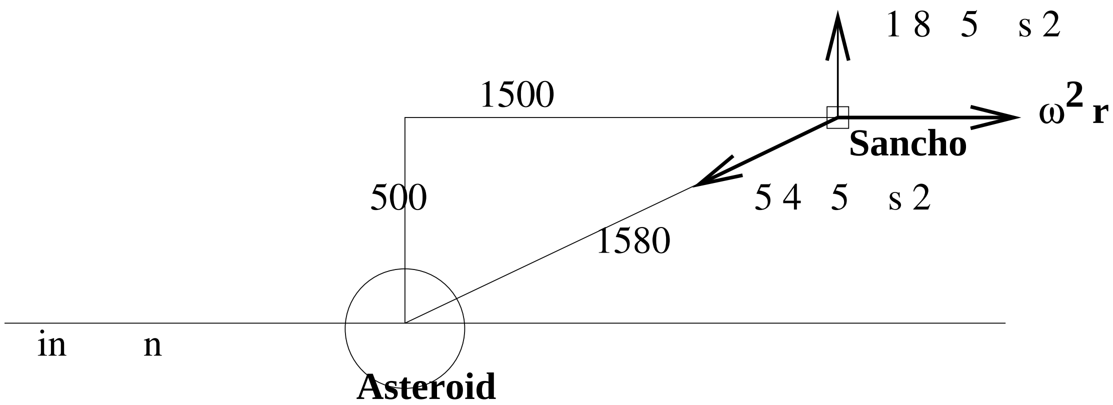
The complement of instruments for Sancho was scientifically significant, including a high resolution camera, an infrared instrument, an accurate transponder for orbit determination, and (in a first version) even a rack of penetrators to deliver accelerometers and seismic sensors to the asteroid; this because the internal structure is also relevant for the response to the impact.

In early 2003 the Don Quijote proposal won the NEOMAP competition, and was officially selected as the mission to be pursued; the second in the ranking was a proposal for a space-based NEO survey.

6.4 The Don Quijote phase A study

The phase A study was conducted lead by Astrium, who studied the bus and the instruments, although some were abandoned, in particular the penetrators.

In the phase A study, we were looking for a safe and stable orbit for Sancho, around a 500 m asteroid. In an asteroid-centric orbit the radiation pressure from the Sun on the S/C is not negligible. I found this simple analytic solution, in which the gravity from the asteroid, the radiation pressure, and the centrifugal apparent force due to a circular orbit can exactly balance for a circular asteroid orbit. (Figure refers to a plane rotating with a fixed angular velocity ω around the direction of the Sun.)



This is a good stable orbit, more complex when taking into account the eccentricity of the asteroid orbit. However, the value of the distance h between the orbit plane and the asteroid center of mass cannot be predicted, given the uncertainty in the radiation pressure: there is a **photogravitational symmetry**.

6.5 The end of the story is not known

How did the Don Quijote project continue? In fact, it was not directly continued by ESA, but other similar missions have been proposed.

NASA took its own initiative, by launching the **Deep Impact** S/C towards a flyby to comet Tempel 1. One day before the flyby, the main S/C released an impactor, which successfully did hit the comet. It was not possible to take an image of the crater after the impact because the main S/C was already too far. Thus another probe, the Stardust S/C, was sent to a flyby with Tempel 1 to observe and measure the crater. This mission did show that NASA has already the technology to overcome difficulty 2., but did not contribute to the other problems of the deflection.

ESA attempted to study, and propose to the member states (as an optional program, only the science programs are funded with the compulsory budget) the AIM-AIDA-DART combined mission, which should have had an ESA “Sancho-like” S/C and a NASA “Hidalgo like” S/C. Unfortunately this proposal was successful in obtaining funding neither in Europe nor in America.

The morale could be that the “pact with the devil” of proposing a planet-defense mission to obtain also a science mission may not work.

7.1 How many different types of asteroid?

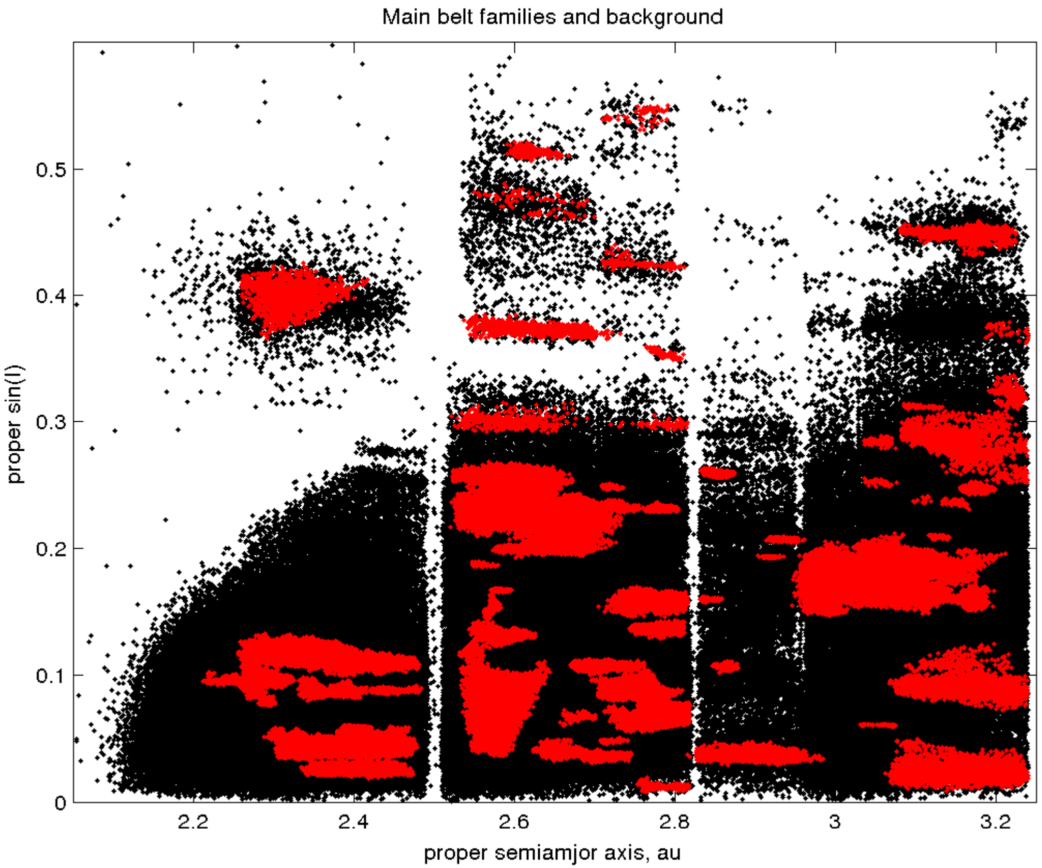
To explain why the scientists are never tired to see a new asteroid, we need to assess the diversity of the asteroid population. Even limiting to Main Belt Asteroids (MBA) there are two partitions: taxonomic classes (supposed different composition) and classification of families (supposed common collisional origin).

Taxonomic classes are defined on the basis of multicolor photometry, spectra, and albedo (mostly from infrared observations). The first order classification lists the S complex with stony asteroids, the C complex with high carbon content, and the V class with basaltic rocks. However, there are less numerous but important groups like the M class, which are supposed to contain mostly pure metal, like in the cores of differentiated bodies.

Moreover, asteroid are also differentiated by size. The largest asteroids are roughly round (equilibrium shape, definition of nanoplanet according to IAU) and may have an internal structure with crust, mantle and core. Small asteroids have a lower density than the large ones of the same taxonomic class, presumably due to porosity (micro and macro).

In conlusion, it is not true that any new asteroid visit is scientifically important, but there are still many asteroids of taxonomic class, albedo and size range, not yet visited.

7.2 Asteroid families



Moreover, the distribution of asteroids in the phase space of orbital elements is very far from being uniform. A plot like this shows the Kirkwood gaps corresponding to the mean motion resonances $3/1$, $5/2$ and $2/1$ with Jupiter, and concentrations of asteroids found in a space of proper elements, which are called (after Hirayama 1916) **asteroid families**. They can be interpeted as asteroids generated by one and the same collisional event, in the geological past (100 My ago and more).

7.3 Proper elements and asteroid families

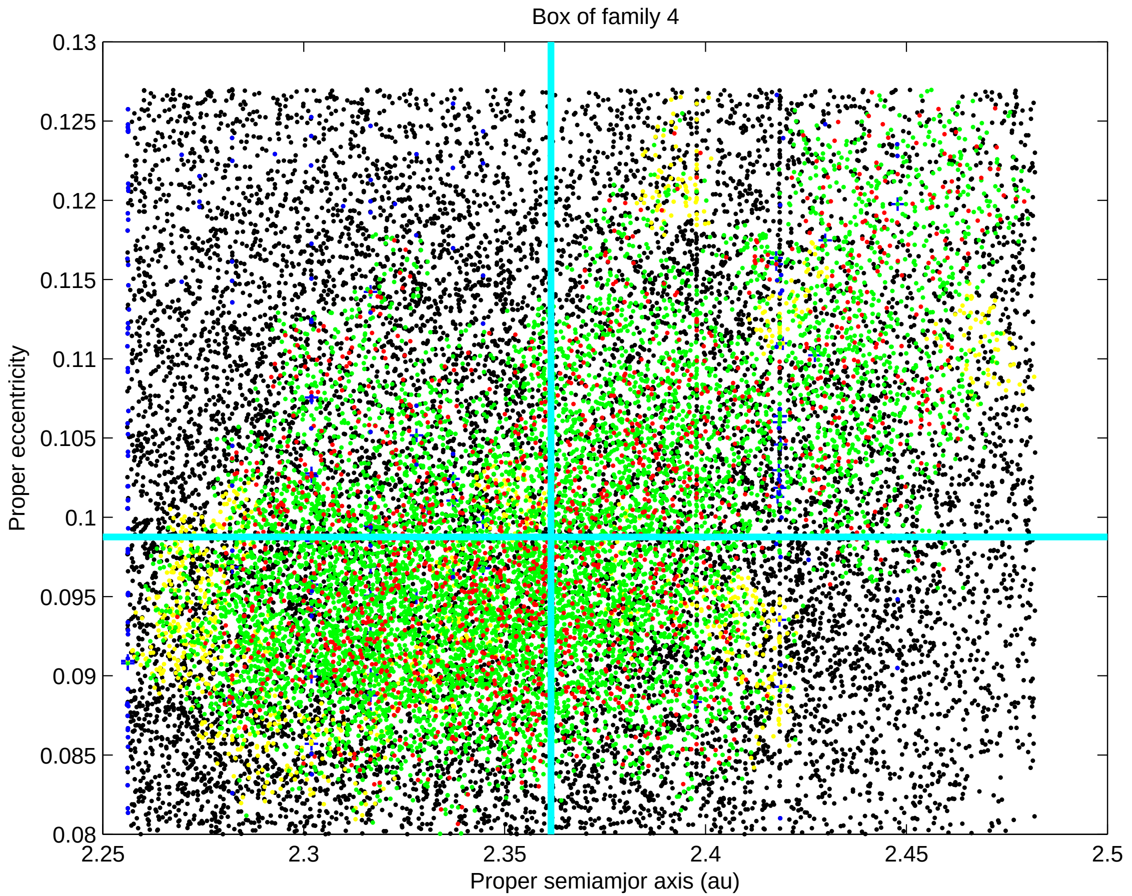
Some Celestial Mechanics, from an operational point of view. Given a catalog of asteroids, for which we have a (good enough) orbit, what can we do to classify them from a dynamical point of view?

Proper elements are parameters corresponding to the action variables, can be called proper a, proper e, and proper $\sin I$, with the key property that they are stable (within a small margin of oscillation) over an extremely long time. Small means that the standard deviations $\sigma(e), \sigma(\sin I)$ and $\sigma(a)/2a$ should be of the order of the ratio (escape velocity/orbital velocity). Long time means 10^6 y, even 10^8 and more if the dynamic model is conservative.

The AstDyS consortium maintains a catalog of synthetic proper elements, with $\sim 541,000$ sets of proper elememts. $\sigma(a)/(2a) < 0.0001$ for $\sim 522,000$, $\sigma(e) < 0.003$ for $\sim 495,000$ and $\sigma(\sin I < 0.001$ for $\sim 487,000$ (all three conditions for $\sim 458,000$).

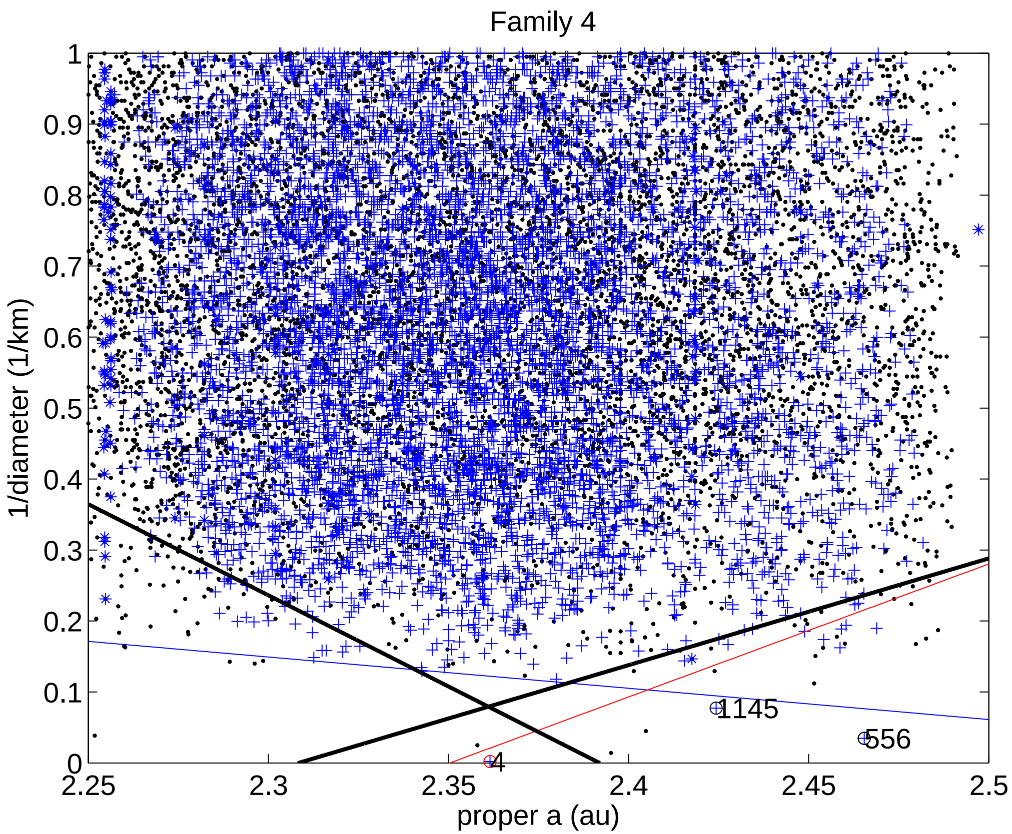
Then, if an asteroid did undergo a collision, even in a remote geological past, the fragments remain together in proper $e, \sin I$, they spread in proper a only because of Yarkovsky effect, a secular perturbation due to thermal emission by the asteroid.

7.4 The Vesta Family



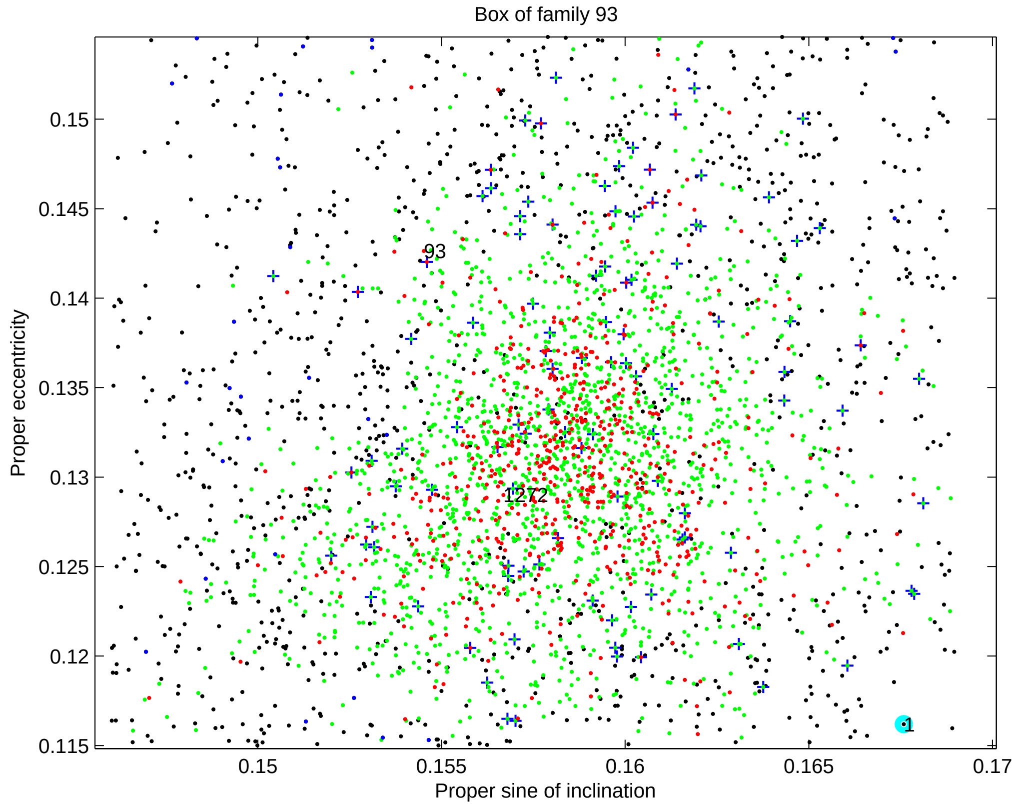
The family with parent body (4) Vesta currently has $10,612$ members; it is of cratering type, the parent body contains $> 99\%$ of the family volume. With respect to the position of (4), marked by cyan lines, the family appears to have (at least) two components, one more dense with lower proper e, one sparse with higher e and a. How should this be interpreted?

7.5 The Vesta Family age



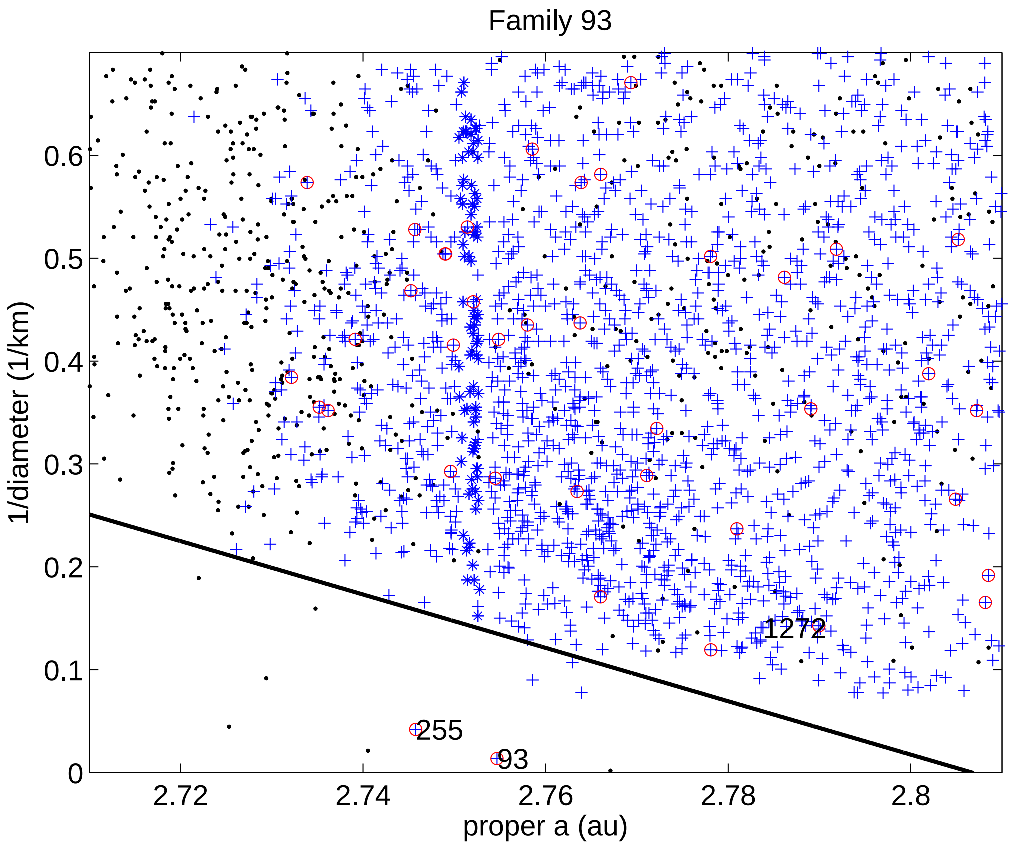
The family members disperse in proper a due to a secular drift, proportional to $1/D$ (diameter), with a maximum of $da/dt = \pm 3.5 \times 10^{-4}$ au/My for $D = 1$ km. Thus the two slopes $\Delta a/(1/D) = -0.335$ on the low a side and $= +0.665$ on the high a side correspond to two different ages $\Delta t = \Delta a/(da/dt) = 930$ My for the low a side and $= 1,906$ My for the high a side. They correspond to the two components of the family seen in the previous figure. Thus there are two collisional families.

7.6 Searching for a Ceres family



The asteroid (1) Ceres does not belong to any family. Attempts to attach it to some other propossed family fail: by its proper elements it is unlikely to belong to family (1272). Why no family? It has an impact cross section larger by > 3 than the one of Vesta, and Vesta has been hit twice in ~ 2 Gy.

7.7 The Gefion family



The V-shape for the family of (1272) Gefion has only one side, the other being eaten up by the very strong $5/2$ mean motion resonance with Jupiter (at $a \simeq 2.82$ au). The dark, C-type asteroids (93) and (255) cannot belong to the family, containing 90% of bright, S-type asteroids. Equally (1) Ceres, with albedo 0.09, cannot have anything to do with this family.

8.1 Claims and ground truth

Our group (PI-BE-TO-NI) has proposed two models, based only on observations from the Earth (or Earth orbit) and our computations (orbit determination, proper elements, family classification, V-shapes fits):

- The Vesta family has two components, with a different age estimates (in a ratio roughly $2/1$), both of cratering type, thus on Vesta there should be two very large craters, also with a different age. (Disclaimer: this prediction was published after the visit to Vesta by DAWN, thus we are not claiming an independent discovery).
- The asteroid (1) Ceres appears to have no family (large enough to be detected, that is > 100 members), while it should have several large families of cratering type. We proposed two possible mechanisms by which Ceres would be very inefficient in generatong asteroid families: either it has a very weak crust, not allowing ejecta reaching an indipendent orbit in one piece, or the crust is very thin, with largerly hydrated material below, leading to families of main belt comets, disappearing in a comparatively short time.

This is a completely different way to obtain a synergy between science and space missions: have theories, will travel to collect ground truth. However, does this require to be part of the mission team? For DAWN, we were not.

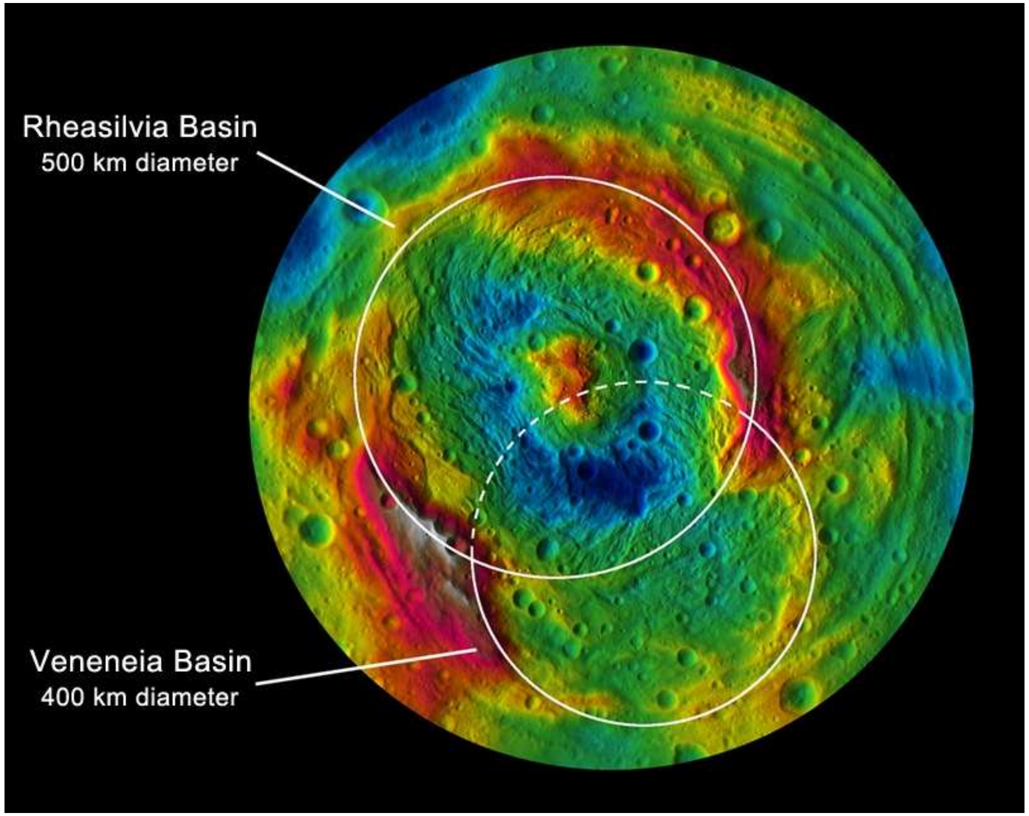
8.2 The DAWN mission

The DAWN mission was enabled by the development of the electrostatic ion thruster, with xenon as propellant. it was flight tested with the NASA Deep Space 1 technological mission. The specific impulse was $3,100$ seconds, about an order of magnitude more than chemical rockets: with 425 kg of propellant, this allowed a ΔV budget of > 10 km/s.

The goal ws to perform a multiple asteroid rendez-vous, each including an extended exploration (by going down to low, circular orbits). The selected targets where the two “nanoplanets” Ceres and Vesta. It carried three instruments, a camera, an imaging spectrometer VIR (manufactured in Italy), and a Gamma Ray and Neutron spectrometer, plus the tracking for gravity.

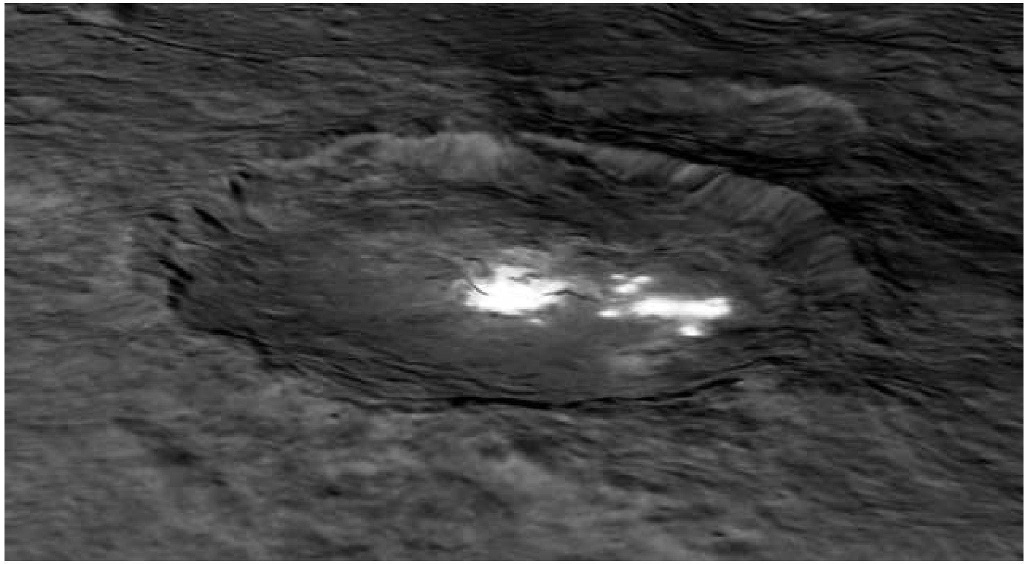
DAWN was proposed as a Discovery mission (different NASA strategy for mission selection), operated by JPL; was selected in 2001, and launched in 2007. It visited Vesta in 2011–2012 and Ceres from 2015 (it is still operating there).

8.3 The DAWN mission at Vesta



One of the most striking features found on the surface of Vesta is a “figure 8” shape around the South pole of the asteroid. it indicates a less ancient crater, named Rhea Sylvia, with a diameter of 505 km, and a partially obliterated more ancient crater of about 400 km, named Veneneia. The age of Rhea Sylvia has been estimated to be about $1,000$ My by crater count; the age of Veneneia must be older, but an accurate estimate has not yet been derived from the DAWN data.

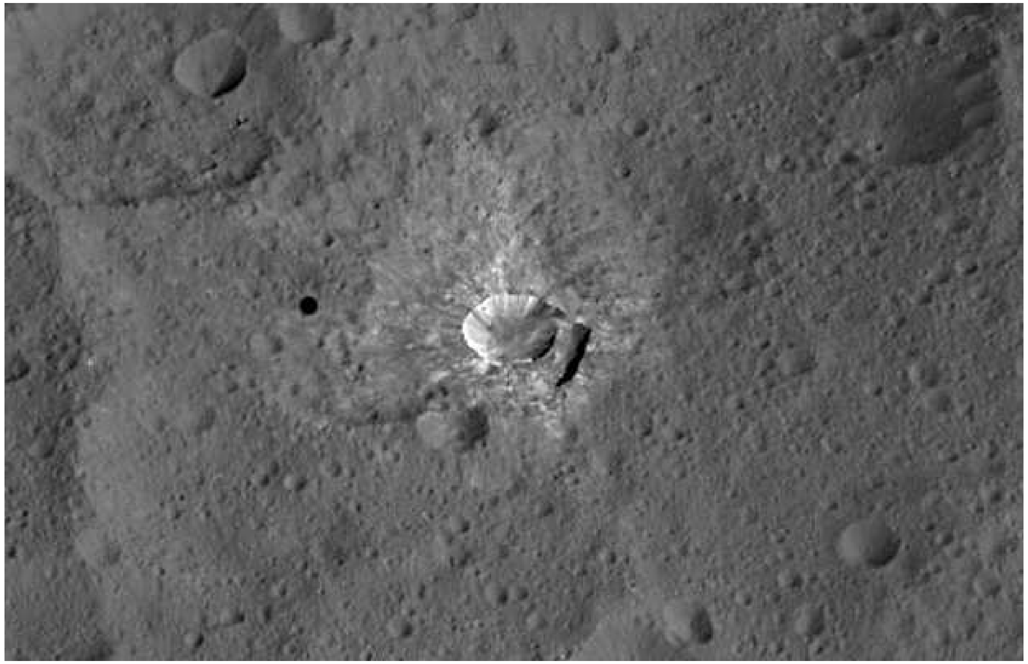
8.4 The DAWN mission at Ceres



On Ceres DAWN has identified > 130 very bright spot, the most prominent near the center of the crater Occator. Salty deposits and even some outcrops of hydrated material have been identified.

Moreover, Ceres shows no ostensible crater with diameter > 280 km; probably, the crust is not rigid enough to sustain such large topographic features. There are planitiae, that is large depresssion which could be interpreted as the shallow remains of larger craters.

8.4 Interpretation of DAWN data



Even much smaller craters, like Oxo (diameter 9 km) have bright ejecta blankets.

Although the interpretation of the DAWN data is still ongoing, we expect that the crust of Ceres will be confirmed to be both not very thick and structurally weak, that is the true the explanation for the lack of a Ceres family should be a combination of the two we have proposed.

9.1 Next asteroid missions: PSYCHE, LUCY

In January 2017 NASA announced the selection of the two next Discovery missions of Solar System exploration, both about asteroids: PSYCHE and LUCY. These missions have a budget of 450 M$ each. European participation is not envisaged yet, but may come later (see DAWN, JUNO).

PSYCHE is meant to visit (16) Psyche, which may be the largest (mean $D > 200$ km) M-class asteroid, composed essentially of metal, and is believed to be a remnant of the core of a much larger asteroid. Mission to be launched in 2022, should rendez-vous with the asteroid in 2030, by using also electric propulsion. It is managed by JPL, the Principal Investigator is from Arizona State University.

LUCY is meant to explore the Trojan asteroid belt, which has never been visited before. Mission to be launched in 2021, visit a MBA in 2025, and 6 Jupiter Trojans in 2027–2033, by using electric propulsion. It is managed by the Goddard Space Flight Center, the Principal Investigator is Dr. Harold F. Levison of Southwest Research Institute.