46th ESLAB Symposium

Formation and Evolution of Moons

Abstract Book &Programme

25- 28 June 2012

European Space Agency
ESTEC
Noordwijk, The Netherlands

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Workshop secretariat:
ESA Conference Bureau
esa.conference.bureau@esa.int

The history of the ESLAB Symposia

Originally European space research was organized through the European Space Research Organization (ESRO) including the European Space Research Laboratory (ESLAB) which was housed in a former hotel in the village of Noordwijkerhout in the Netherlands. ESLAB later became ESA's Space Science Department (SSD) and located at the European Research and Technology Centre (ESTEC), and subsequently became the Research and Scientific Support Department (RSSD). However the original name survives in the annual ESLAB Symposia which are organized for the benefit of European science as well as promoting working relations between ESA's scientific staff and the community they support.

For those attending their first ESLAB symposium, what is behind the name? (Incidentally, some participants may actually be younger than ESLAB – this is the 46th meeting!)

RSSD is part of the Directorate of Scientific and Robotic Exploration of ESA. It is often called the main interlocutor between ESA and its scientific community and, indeed, its prime function is to provide Project Scientists. They ensure that ESA missions fulfil their original scientific goals, and work with the principal investigators and their experiment teams, as well as with the Project Managers (who belong to another Department of our Directorate, the Scientific Projects Department) in the continuous process of optimising a mission and balancing scientific, technical and financial considerations. RSSD also provides the Study Scientists for potential future missions.

The Department also provides a scientific environment in which its staff can perform their own, original research. This is, in our view, mandatory if they are to stay in touch with the reality of the scientific process, the arduous step-by-step progress towards new knowledge.

We are in the happy position of being able to choose an entirely different topic for each ESLAB Symposium. Sometimes we decide to look at a specific mission, be it during its scientific preparation or, after flight, at its results, and sometimes on the future technology needed to carry out innovative new projects. This year we decided to focus on the formation and evolution of moons in the solar system. As of today, 170 moons orbit six of the eight planets, while 7 moons orbit three of the five dwarf planets. Numerous moons have been discovered around asteroids and Trans-Neptunian objects. Also, there are large numbers of small moons embedded within Saturn's rings. Understanding the formation and evolution of the natural satellites of the planets is important, as a piece of the wider puzzle concerning the formation and evolution of the solar system as a whole. Significant progress has been achieved recently on the formation of the Moon and of the regular satellites of the giant planets. However, many questions regarding the different formation mechanisms are still unanswered. The goal of the symposium is to review all possible scientific mechanisms for forming the moons, and for driving their subsequent evolutions, and their consequences on our current understanding of solar system formation and evolution.

Programme

Monday 25 June 2012

12:00-14:00: Registration, posters set up

14:00 – 14:20 Welcome and opening remarks (O. Witasse, L. Colangeli)

Session 1 – Formation mechanisms: Moons of giant planets
Moderator: *A. Coustenis*

14:20 Moon formation in the context of solar system formation
A. Coustenis

14:30 Origin and evolution of Galilean satellites *INVITED*
O. Grasset

15:00 On the Origins of the Regular Satellites of Gas Giant Planets *INVITED*
P. Estrada

15:30 Final origin of the Saturn system
E. Asphaug

15:50 Coffee break

Session 1 – Formation mechanisms: Moons of giant planets
Moderator: *D. Richardson*

16:20 The spreading of a tidal disk as a new mechanism for satellite formation: The case of Saturn's satellites and rings and implications for Saturn's dissipation.
S. Charnoz

16:40 A general model for satellite formation: the spreading of massive rings
A. Crida

17:00 The anelastic equilibrium tide in Solar System
F. Remus

17:20-18:00 Discussion

18:15 Welcome reception (sponsored by HE Space)

Tuesday 26 June 2012

Session 1 – Formation mechanisms: Moons of Giant planets (following)
Moderator: *S. Charnoz*

09:00 The Formation Environment of the Galilean Moons
N. Turner

09:20 Dynamics of the small Saturn's moons in coupled resonances
M. El Moutamid

09:40 A study of small satellites capture in corotation resonance
E. Vieira Neto

10:00 Satellite Origin and Evolution via Three-body Encounters *INVITED*
C. Agnor

10:30 Coffee break

Session 2 – Mechanisms of formation: Moons of terrestrial planets
Moderator: *P. Estrada*

11:00 Recent advances in formation of moons of terrestrial planets
P. Estrada

11:10 On the Formation of the Martian Moons from a circum-Mars accretion disk
P. Rosenblatt

11:30 New results on the formation of the Moon: 100-years accretion timescales and implications for Earth-Moon isotopic similarities *INVITED*
J. Salmon

12:00 Possibility of Moon formation from debris escaped after impacts on the Earth
W. Svetsov

12:20 Earth's minimoons
M. Granvik

12:40 – 13:10 Discussion

13:15 -14:30 Lunch

Session 3 – Formation mechanisms: Pluto, KBOs & Asteroid systems
Moderator: *E. Asphaug*

14:30 Multi-bodies systems
E. Asphaug

14:40 Modeling the Collisional Origin of Satellites around Large KBOs *INVITED*
Z. Leinhardt

15:10 Formation of Pluto's small satellites *INVITED*
H. Levison

15:40 Formation scenarios of asteroid binaries and implications for the science return of the MarcoPolo-R mission *INVITED*
P. Michel

16:10 Numerical Simulations of Small Solar System Binary Formation
D. Richardson

16:30-17:00 Discussion

17:00-18:30 Coffee break and poster session

List of posters:

Why Mercury and Venus do not have a Moon?
J. Benkhoff

Statistical co-accretion model of formation and composition of prelunar swarm
G. Pechernikova

Impact craters: the evolutionary leaders
E. Martellato

Extra high underground temperature of oceanus procellarum revealed by Chang'e-1 lunar microwave radio meter data
W. Zhang

A possible reason why moon doesn't have a significant dipolar magnetic field
W. Zhang

Modeling and measuring the mass distribution inside Phobos to constrain its origin.
A. Rivoldini

A database of elongated craters on Mars to study the falling moonlet hypothesis
B. Buchenberger

Tidal displacements of Phobos' surface: A key information to reveal its origin
S. Le Maistre

Deimos and Phobos compared observations by OMEGA/MEX.
B. Gondet

How to improve the orbit model of Phobos using observations with ALMA?
E. Villard

Stratospheric Observatory for Infrared Astronomy Capabilities for Observations of Moons
M. Burgdorf

Interaction of Phobos' surface with the Solar Wind and the Martian Environment
F. Cipriani

SCF_LAB: an infrastructure to characterize laser altimetry of icy and rocky moons
S. Dell'Agnello

A high resolution orbitrap mass spectrometer for future moon missions
S. Cornelli

A New Numerical Model for multiple systems : ODIN
L. Beauvalet

Charged Nanograins in the Plume of Enceladus
G. Jones

Wednesday 27 June 2012

Session 4 – Moons atmosphere, environment and evolution
Moderator: *M. Dougherty*

09:00 Interaction between moons and their environment
M. Dougherty

09:10 The origin and evolution of Titan's atmosphere *INVITED*
A. Coustenis

09:40 Io: A (geo-)physicist's playground *INVITED*
N. Thomas

10:10 Satellite-Magnetosphere Interactions *INVITED*
G. Jones

10:40 Plasma interactions at Titan and icy moons: evolving ionospheres
A. Coates

11:00 Coffee break

11:30 Surface radiation environment of Saturn's icy moon Mimas
T. Nordheim

11:50 Magnetospheric Ion Implantation in the Icy Moons of Giant Planets
G. Strazulla

12:10 Ridge formation and de-spinning of Iapetus via an impact-generated satellite
K. Walsh

12:40 – 13:10 Discussion

13:15 -14:30 Lunch

Session 5 – Observational constraints
Moderator: *J.-P. Lebreton*

14:30 Observations for origin and evolution of moons
J.P. Lebreton

14:40 Depth of Enceladus craters: implications of surface properties on the early differentiation of icy moons
K. Degiorgio

15:00 Mimas and Enceladus: Formation and interior structure from astrometric reduction of Cassini images.
R. Tajeddine

15:20 Constraints on Moon evolution and planetary processes using SMART-1 data
B. Foing

15:40 Mars Express investigations of Phobos
O. Witasse

16:00 Coffee break

16:30 The origin of the Martian moons revisited
P. Rosenblatt

16:50 The age of Phobos *INVITED*
G. Neukum

17:20 Meteorite Analogs for Phobos and Deimos: Unraveling the origin of the Martian moons
P. Vernazza

17:40 – 18:00 Discussion

19:00 Dinner Restaurant "Het Zuiderbag", Noordwijk

Thursday 28 June 2012

Session 6 – Future missions and Instrumentation
Moderator: *P. Rosenblatt*

09:00 Future exploration of moons
P. Rosenblatt

09:10 Future plans for Cassini
N. Altobelli

09:30 New Horizons *INVITED*
H. Levison

10:00 JUICE: an ESA L-mission to the Jupiter system *INVITED*
O. Grasset and M. Dougherty

11:00 Coffee break

11:30 Science and payload activities in support of the ESA Lunar Lander
J. Carpenter

11:50 The Martian Moon Sample Return mission study MMSR
D. Koschny

12:10 GETEMME: a mission to explore the Martian satellites
C. Le Poncin-Lafitte

12:30-13:00 Discussion

13:00-13:15 General conclusions

13:15 END OF THE MEETING

ABSTRACTS

Origin and evolution of Galilean satellites

O. Grasset, *Nantes University, France*

On Jupiter, the limited composition information available favours the core accretion hypothesis for its formation (Lunine et al., 2004), possibly with subsequent radial migration of planetary orbits (Tsiganis et al. 2005). In this scenario, Jupiter formed a core of approximately 10 Earth masses, through accretion of the icy planetesimals. The limited lifetime of the Solar Nebula, constrained to about 10 Ma through astronomical observations of circumstellar disks around nearby stars (Meyer et al., 2006), poses a strict constraint to the formation time of the core and the accumulation of gas. Accretion of gas and solid material into JupiterÕs envelope works through the formation of a sub-nebular disk, and it is within this disk that formation of regular satellites by accretion of solids is believed to take place. Their further differentiation, should be almost completed before the complete decay of 26Al, namely between 2.5-5.0ÊMa. But later differentiation might still be possible (Barr and Canup, 2010). The relationship between the formation of the Galilean satellites and that of Jupiter is still unclear. The different scenarii which can be proposed, as well as the different constraints that are still missing for understanding in greater details the origin of the moons will be reviewed.

The Galilean moons are the largest moons of the Jovian system. Io is a rocky moon, sulphur-rich, and it possesses the most active volcanism in the Solar System. The three other moons are made of iron, silicate, and ice, well differentiated in the case of Ganymede and Europa, but not fully separated in Callisto. GalileoÕs detection of induced magnetic fields combined with imaged surface characteristics and thermal modeling of the moons' evolution, advocate the presence of liquid water oceans below the icy crusts. Here, tidal dissipation and radiogenic energy keep the water liquid (Hussmann et al., 2006). However, the depth and composition of the oceans, as well as the dynamics and exchange processes between the oceans and the deep interiors or the upper ice shells, remain unclear. Part of the story is linked to the fact that Io, Europa, and Ganymede are locked in a mean-motion resonance unique in the Solar System, the Laplace resonance in which the orbital periods of the satellites are in the ratio 1:2:4. It is still unclear how and when the resonance formed. It might be of primordial origin (Peale and Lee 2002) or formed by orbital expansion of the satellites due to tides and subsequent capture into resonance as a result of the decreasing speed of orbital expansion with increasing distance from Jupiter (Yoder and Peale 1981). The Laplace resonance determines the amount of tidal dissipation in the satellites since it maintains finite orbital eccentricities, required for tidal interactions, on geological timescales. As tidal dissipation can be an important heat source for the satellites, and is by far the largest energy source for Io, gravitational interactions drive internal dynamics and evolution of the satelliteÕs interior and surface. The different models of evolution will be discussed.

On the Origins of the Regular Satellites of Gas Giant Planets

P. Estrada, *NASA Ames Research Center, MS 245-3, Moffett Field, CA, USA*

Over the last quarter century, a more clear picture of outer planet satellite systems has emerged thanks in great part to the success of the Voyager, Galileo, and Cassini missions. These spacecraft have served to provide a wealth of observational constraints from which to construct viable models for satellite formation. Furthermore, the cosmochemical and dynamical properties of the satellites may provide important clues about the late and/or post-accretional stages of giant planet formation. This is particularly relevant because considerable progress in our understanding of giant planet formation and their associated circumplanetary disks continues to be made. These improvements, which allow us to directly tie the formation of the satellites to their respective parent planet, along with better observational constraints, has ultimately provided the basis for a self-consistent satellite formation scenario from which we can begin to make direct, meaningful comparisons between the diverse families of giant planet moons in our solar system.

We will primarily discuss a self-consistent model in which the satellites of the giant planets form in a two-component gaseous subnebula: a relatively dense, compact inner region that forms as a result of the accretion of low specific angular momentum gas during a period after envelope contraction and prior to opening a deep gap in the solar nebula; and, a more radially extended lower-density tail which arises as a result of the continued gas inflow through a deep gas gap as the planet approaches its final mass. The resulting disk may be initially quite massive as one might expect from a rough equipartition of angular momentum between the planet and disk, but the subnebula is expected to evolve viscously, driven by the inflow itself, until the gas inflow wanes in the gap-opening timescale. In this picture, satellite formation occurs at the tail end of planetary accretion by which time sufficient gas has been removed from an initially massive subnebula, and turbulence in the circumplanetary gas disk decays.

Some of the key issues of this model that will be addressed include the satellite mass and angular momentum constraints, the role of turbulence, and the source of solids for satellite accretion. In particular, we will discuss recent work that ties the properties of nebula planetesimals to subnebula satellitesimals and ultimately the satellites themselves, providing a direct link between the solar nebula and the subnebula. We will discuss key parameters of the model such as disk temperature, satellite accretion and migration timescales. Satellite growth in this model is inherently non-local, with satellites located in the extended outer disk taking longer to accrete than those in the inner regions. This is because the timescale of accretion is set by inward gas-drag drift time of satellitesimals of different sizes, which can simultaneously explain empty regions of the circumplanetary disks as well as, for example, the capture of Hyperion into resonance with Titan. Finally, we will discuss several specific observations that lend strong support to this model view.

Final Origin of the Saturn System

E. Asphaug, *UC Santa Cruz,* **and A. Reufer,** *University of Bern*

Saturn is orbited by a half dozen middle-sized icy satellites of diverse geology and composition, accounting for 4.4% of the system mass, and has one Galilean-sized satellite, Titan. Jupiter on the other hand has no middle-sized moons (MSMs) at all, but has four Galilean satellites that account for all but 0.002% of the system mass. The inner three are in a Laplace mean motion resonance, thought to have evolved into this coordination shortly following their formation.

According to Peale and Lee (2002) and Ogihara and Ida (2012), Laplace-like resonances appear to be a common outcome for Canup-Ward (2002) mechanisms of Galilean satellite formation. Considering that Titan is somewhat more massive, per planet, than Jupiter's satellites combined, we consider whether Saturn might have begun with its own Laplace-like resonant chain of ~3-4 Galilean satellites, which collapsed into one larger merged satellite, Titan, in response to a final dynamical instability. The MSMs would be a byproduct, and a record, of these final mergers.

We support our hypothesis with SPH simulations showing that Galilean satellite mergers liberate ice-rich spiral arms. These arms self-gravitate into MSM-sized bodies of diverse composition, with energetic rotations. They derive mostly from the ice-rich outer layers of the smaller of the two colliding satellites; some incorporate materials from kilobar pressures. Because they are launched on escaping but satellite-crossing orbits, they must ultimately avoid reaccumulation with Titan, and this presents a fundamental challenge to our model.

Middle-sized moons also have to survive the Late Heavy Bombardment, if there was one, so it is not surprising to find MSMs absent at Jupiter, or only their relics. If the same underlying causes of the LHB led to the proposed final satellite merger around Saturn, then the MSMs and the geology of Titan would postdate the peak of the bombardment.

We will evaluate our model in comparison to other models for MSM formation, including disk models (Canup 2010; Charnoz et al. 2011) and hit and run models (Sekine and Genda 2012). All have dynamical, statistical, and geophysical challenges. We explore the details of a final Titan-forming merger, and argue that our model is well supported by the geological activity and dynamical excitation of Saturn's moons.

The spreading of a tidal disk as a new mechanism for satellite formation : The case of Saturn's satellites and rings and implications for Saturn's dissipation.

S. Charnoz, *Laboratoire AIM / Universite Paris Diderot/CEA /CNRS*, **and A. Crida,** *Laboratoire Lagrange / Univ Nice Sophia-antipolis / CNRS / Obs. Cote d'Azur*

The origin of Saturn's satellite is largely debated and models of the formation of the inner moons in Saturn's primordial nebula in general fail to explain (i) the abundance of volatile elements and (2) the very ordered orbital architecture of the inner moons. It has been suggested recently (Charnoz et al., 2010) that some of the smallest moons may have accreted from the slow spreading of Saturn's rings, from the material that crossed the Roche Limit. Using a new type of hybrid simulation, the disk's spreading as well as the satellite accretion and the planet's tides were coupled. As a result the orbital architecture of the satellites was recovered. More recently (Charnoz et al., 2011) the model was extended to the totallity of Saturn's inner moons (up to Rhea) designing a full new view of satellite formation, implying that Saturn's rings were massive in the past and that Saturn's dissipation was about 10 times more intense than usually assumed, so that Q~2000 is needed in agreement with recent astrometrical work (Lainey et al., AOJ, 2012). Among the strange properties of this new mechanism, through an heterogeneous accretion mechanism, it is easy to form differentiated satellite without the need of radiogenic heating (explaning Enceladus for example) and to implant silicates in some of the icy moons. I will review this model, its main properties and its implication in terms of dynamics, timescales and geology and its implication for the history of the rings. I will also talk about Saturn's dissipation and the necessity to revise Saturn's Q. Then I will draw a link with the formation of the Earth's Moon showing that it is fundamentally the same process.

A general model for satellite formation: the spreading of massive rings

A. Crida, *Laboratoire Lagrange / Univ Nice Sophia-antipolis / CNRS / Obs. Cote d'Azur,* **and S. Charnoz,** *Laboratoire AIM / Universite Paris Diderot/CEA /CNRS*

This talk is devoted to satellite formation from the spreading of a debris disk initially confined inside the Roche radius of the planet (hereafter « tidal disk »). Beyond the Roche radius, solids aggregate, forming new moons that migrate outward because of the disk's gravitational torque. Recently, Charnoz et al. (2010, 2011) showed with numerical simulations that the physical properties of Saturn's regular satellites inside Titan's orbit can be explained if they were born from the spreading of the rings. I will present an analytical model of this process, and show that it applies as well to Uranus, Neptune, the Earth, Pluto, and possibly Mars.

We demonstrate that if the disk's life-time is long (which would be the case for a massive ring around a giant planet), migration is faster than accretion, and many satellites form and migrate away. During this phase, mergers take place in a hierarchical way, so that the final mass-distance distribution of the satellites should follow a particular law. This law is found to be in very good agreement with the present (an peculiar) distributions of the inner satellites of Saturn, Uranus, and Neptune.

Conversely, if the spreading is fast (the disk's life-time is short), then accretion is faster than migration, and the entire disk's material gathers into one large satellite, possibly with a smaller companion. This is the case of a debris disk created by a giant impact on a terrestrial planet, and is consistent with the latest Moon formation models.

Therefore, we suggest that most regular satellites in the Solar System formed from the spreading of a tidal disk, and that terrestrial and giant planets satellites systems can be unified in this new paradigm for satellite formation.

The anelastic equilibrium tide in Solar System

F. Remus, S. Mathis, J-P Zahn, *Observatoire de Paris – LUTH, Meudon,* **and V. Lainey,** *Observatoire de Paris / IMCCE*

Once a planetary system is formed, its dynamical evolution is governed by gravitational interactions between its components, be it a star -planet or planet-satellite interaction. By converting kinetic energy into heat, the tides pertub their orbital and rotational properties, and the rate at which the system evolves depends on the physical properties of tidal dissipation. Therefore, to understand the past history and predict the fate of a binary system, one has to identify the dissipative processes that achieve this conversion of energy.

The Solar System displays a large diversity of planets, with telluric planets having anelastic mantles and giant planets with possible anelastic cores. As for the fluid parts of a planet, the tidal dissipation of such solid regions, gravitationally perturbed by a satellite, highly depends on its internal friction, and thus on its internal structure. Therefore, modelling this kind of interaction also presents a high interest to provide constraints on planets interiors, whose properties are still quite uncertain.

Here we examine the equilibrium tide in the solid part of a planet for any rheology, taking into account the presence of a fluid envelope. We first present the equations governing the problem, and show how to obtain the different Love numbers that describe its deformation. We discuss how the quality factor Q depends on (1) how the shear modulus varies with tidal frequency, (2) the radius, and (3) the rheological properties of the solid core.

Taking plausible values for the anelastic parameters, and discussing the frequency and core size dependences of the solid dissipation, we show how this mechanism may compete with the dissipation in fluid layers, when applied to Jupiter- and Saturn-like planets. We also discuss the particular case of the icy giants Uranus and Neptune.
Finally, we show how the results may be implemented to describe the dynamical evolution of planetary systems.

The Formation Environment of the Galilean Moons

N. Turner, *MPIA Heidelberg and JPL/Caltech,* **M. H. Lee,** *Hong Kong University,* **and T. Sano,** *Osaka University*

We show that the disks of gas and dust orbiting gas giant protoplanets are subject to turbulence driven by the magneto-rotational instability, provided (1) sufficient X-rays reach them from the vicinity of the host star, and (2) the surface densities are substantially less than in minimum-mass models constructed by augmenting Jupiter's satellites to Solar composition, but not so low that ambipolar diffusion decouples the neutral gas from the plasma. We compute the conductivities in a range of circumjovian models, treating ionization by protosolar X-rays, interstellar cosmic rays, and radionuclide decay. Charge transfer to gas-phase metals is included. Recombination occurs in dissociative and radiative gas-phase reactions and on grain surfaces. The results provide support for both minimum-mass and gas-starved models of the protojovian disk: (1) The minimum-mass models have negligible internal angular momentum transfer by magnetic forces, as required for the material to remain in place while the satellites form. (2) If stellar X-rays reach the planet, the gas-starved models have magnetically-active surface layers and a decoupled interior "dead zone", analogous to the Solar nebula. The active layers yield accretion stresses in the range assumed in constructing the gas-starved models.

Dynamics of the small Saturn's moons in coupled resonances

M. El Moutamid, *LESIA, Observatoire de Paris, UMR 8109 du CNRS, 5 place Jules Janssen, 92195 Meudon, France / IMCCE, Observatoire de Paris, UMR 8028 du CNRS, 77 avenue Denfert-Rochereau, 75014 Paris, France*, **B. Sicardy**, *LESIA, Observatoire de Paris, UMR 8109 du CNRS, 5 place Jules Janssen, 92195 Meudon, France / Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France / Université Pierre et Marie Curie, 4 place Jussieu, 75005 Paris, France*, **and S. Renner**, *IMCCE, Observatoire de Paris, UMR 8028 du CNRS, 77 avenue Denfert-Rochereau, 75014 Paris, France / Université Lille 1, Laboratoire d'Astronomie de Lille, 1 impasse de l'observatoire, 59000 Lille, France*

Many satellites in the Solar System are involved in mean motion resonances. The simplest case of all is that of two satellites, one of them with negligible mass (test particle), orbiting in the same plane and close to a mean motion first order resonance of the type m+1:m. In this situation, two critical resonant angles appear, respectively called the Corotation Eccentric Resonance (CER) and the Lindblad Eccentric Resonant (LER) arguments. Each of them has very different physical effects on the test particle, but surprisingly, no general treatment of the coupling between these two resonances has been presented so far in the literature. Here we present a generic dynamical study of this coupling, that we call the CoraLin model. It uses non-dimensional quantities, and describes all possible configurations between the satellites near horizontal first order mean motion resonances. We apply this model to several recently discovered small Saturnian satellites dynamically linked to Mimas through first mean motion resonances : Anthe, Methone and Aegaeon, all associated with ring arc material. The presence of these three structures are consistent with their confinement by CER with Mimas: Aegaeon is trapped in an inner 7:6 CER with Mimas, while Anthe and Methone are respectively near the outer 14:15 and a 10:11 CER resonances. All satellites are also perturbed by the associated LER's, in a way described by the CoraLin model. Poincaré surfaces of section reveal the dynamical structure of each orbit, and for some of them, their proximity to chaotic regions. Those sections may reveal the dynamical origin of those bodies. In particular, we discuss the probability of capturing a satellite into one of the CER's with Mimas as the orbit of the latter evolves through tidal effects. We will discuss the potential implications of this work, in particular the constraints it may provide on Mimas' orbital evolution.

A study of small satellites capture in corotation resonance

E. Vieira Neto, N.C.S. Araujo, *Univ. Estadual Paulista / UNESP***, and B. Sicardy,** *LESIA, Observatoire de Paris, UMR 8109 du CNRS, 5 place Jules Janssen, 92195 Meudon, France / Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France / Université Pierre et Marie Curie, 4 place Jussieu, 75005 Paris, France*

The satellite and ring systems of Saturn are an splendid laboratory to study satellites formation and their dynamics. In the Saturnian system resonances make a play role as we can see in many features in the rings and in the behaviour of the satellites. It is very important to understand the resonances interactions in order to have a knowledgement of the characteristics of the satellites of Saturn and how they were formed. In this work we study the corotation resonance, which occurs when the pattern speed Ωp, the frequency of a reference frame, is commensurable with the orbital frequency of a satellite. In the Saturnian system there are three satellites, Aegaeon, Anthe and Methone which are in corotation resonance with Mimas. We developed a code to numerically study the corotation resonance of Aegaeon with Mimas while Mimas migrates in the Saturnian system. Our preliminary result shows Aegaeon moving together with Mimas as it migrates manteining the corotation ressonance. We investigate the influence of the migration speed in this process and we will show the effects of this migration in the corotation arcs and its consequences in the Aegaeon formation.

Satellite Origin and Evolution via Three-body Encounters

C.B. Agnor, *Queen Mary University of London*

Virtually all models of giant and terrestrial planet formation suggest that close encounters between three (or more) bodies are common. As satellite formation and planet formation are co-evolutionary processes, satellites inherit the accretion environment of their parent planet. Consequently, three-body encounters represent a general and fundamental process affecting the origin and evolution of satellites. These encounters produce a variety of outcomes including physical collision, temporary capture, disruption of a previously bound pair and the exchange of orbiting companions. In this talk I will discuss the general dynamics and outcomes of three-body encounters expected during planetary formation. I will review recent work on the capture of satellites in the outer solar system (e.g., Triton and other irregular satellites) and discuss how three-body encounters affect the evolution of terrestrial planet satellites and the Martian satellites, in particular.

On the Formation of the Martian Moons from a circum-Mars accretion disk

P. Rosenblatt, *Royal Observatory of Belgium, Brussels*, **and S. Charnoz**, *Laboratoire AIM / Universite Paris Diderot/CEA /CNRS*

We reconsider two scenarios for the formation of Phobos and Deimos from a circum-Mars accretion disk of debris: the strong tide regime for which accretion occurs close to the planet at the Roche limit and the weak tide regime for which accretion occurs farther from the planet. We assume a disk with an initial mass of 10^{18} kg (Craddock R.A. [2011], Icarus 211, 1150-1161). In the strong tide regime, the disk loses its material by viscous spreading inward to and outward from the planet. When outward moving material crosses the Roche limit, small-sized moonlets are accreted from gravitational instabilities with a shape and density similar to Phobos and Deimos. Due to the gravitational torque exerted by the disk, the moonlets migrate away from the planet, though they cannot reach the synchronous orbit (lying at 6 Mars' radii), and after the disk has lost most of its mass they rapidly fall back onto Mars due to the tidal decay of their orbits. Although, the total mass of moonlets is comparable to the mass of Phobos, their survival time does not exceed 200 Ma, which is incompatible with the formation of Phobos and Deimos early in Mars' history. In the weak tide regime, moonlets can accrete near the synchronous orbit with the mass of Deimos in a disk of up to 10^{18} kg (similarly to runaway growth of planetesimals in the protoplanetary disk). A Phobos-mass embryo can also be formed in the same disk but closer to Mars (at 3 to 4 Mars' radii) so that it rapidly falls back onto Mars by tidal decay of its orbit. However, several embryos may accrete together in the disk, and Phobos and Deimos may be the last two remnants of those bodies formed near the synchronous distance to Mars. Further investigations are still needed to understand such accretion mechanism within a circum-Martian disk primarily extending below the synchronous orbit.

New results on the formation of the Moon: 100-years accretion timescales and implications for Earth-Moon isotopic similarities

J. Salmon and R. Canup, *Southwest Research Institute, Boulder*

Previous models of the formation of the Moon from a circumterrestiral disk resulting from a giant impact predict that the Moon would form in less than a year (e.g., Ida et al. 1997; Kokubo et al. 2000). Such accretion timescales appear to imply a fully molten Moon, which seems in contradiction with the lack of global faults on the Moon. Also, such a rapid assembly would preclude chemical equilibration of the lunar-forming material with the Earth's atmosphere, which requires $>10^2$ years (Pahlevan & Stevenson 2007). In contrast, post-impact equilibration appears necessary to account for the identical oxygen isotopic compositions of the Earth and Moon. However, prior lunar accretion models may not have been sufficiently accurate, because they represented the disk as a collection of solid particles. Instead, much of the material in the inner disk would have been in the vapor phase - due to both the energy of the impact and the high rate of viscous dissipation expected in the disk interior to the Roche limit - and a disk that is partially vapor would evolve more slowly that a disk of solid particles (Thompson & Stevenson 1988; Ward 2012).

We have developed a new lunar accretion model in which disk material within the Roche limit is represented by a continuous fluid disk, while outside the Roche limit individual particles orbit and accrete into the Moon. We performed numerical simulations using this hybrid fluid - N-body code (based on the symplectic integrator SyMBA; Duncan et al. 1998) taking into account the viscous spreading of the inner disk, tidal accretion criteria for collisions between outer particles, and resonant interactions between the inner disk and the outer moonlets at the strongest Lindblad resonances. When the inner disk extends past the Roche limit, we allow it to spawn new moonlets that are added to the N-body code.

We find that the accretion of the Moon proceeds in 3-stages: (1) bodies initialy outside the Roche limit collide and accrete in less than a year, (2) a few large outerbodies confine the inner disk within the Roche limit due to resonant interactions, and in turn recede away from the disk, and (3) the inner disk slowly spreads back out to the Roche limit and spawns new moonlets that complete the growth of the Moon. We find that the slow spreading of the inner disk in stage (3), which is limited by its ability to radiate the heat generated by local gravitational instabilities (Thompson & Stevenson 1988), increases the Moon's final accretion timescale to several hundreds of years. If equilibration occurs between the Earth and inner disk atmospheres, we find that the mass fraction of the Moon composed of equilibrated material is < 50%. However, this material is preferentially accreted during the last stage of the Moon's formation, and so it could be concentrated in the Moon's outer layers and strongly influence the Moon's observed composition, depending on the degree of mixing in the Moon's interior during stage (3).

Possibility of Moon formation from debris escaped after impacts on the Earth

V. Svetsov and G. Pechernikova, *Institute for Dynamics of Geospheres / Russian Academy of Sciences*

Large impacts happened during the whole period of Earth accumulation. We consider the possibility that the Moon originated from debris produced by these numerous impacts (in contrast to the widely accepted theory of Moon formation due to a single giant impact). The co-accretion hypothesis of Schmidt-Safronov-Ruskol predicts that, when planetesimals collided within the Hill sphere of the Earth, some of the fragments with high angular momentum remained in orbits around the Earth. These fragments formed a proto-lunar swarm beyond the Roche limit, which was fed by particles from incoming planetesimals. However, this model meets difficulties with accumulation of ample mass in the proto-lunar swarm. It predicts formation of satellite systems with total mass of no more than 0.01 per cent of the planet's mass. However, the proto-lunar swarm can be fed by debris from the impacts on the Earth. We numerically simulated large impacts on the growing Earth, using a 3D hydrodynamic code, in order to answer some important questions: What is the total mass of debris which is ejected to Earth-bound and heliocentric orbits after large impacts on the Earth? What are the sizes of fragments? Can the debris interact with a swarm of particles rotating around the Earth and contribute to its growth?

The radii of stony impactors in the numerical simulations were from 0.025 to 0.3 of the radius of growing Earth. The velocity of impactors at infinity was half of the Earth escape velocity (a typical value for the accretion period) and the impact angles varied from 0 (head-on impacts) to 90 degrees. Ejecta from head-on impacts are almost completely retained by the planet because of relatively low impact velocities. But oblique and grazing impacts produce fragments which escape the Earth gravity. The total angle-average escaped mass is about 10% of the retained mass. Much smaller mass (0.5-0.8%) is ejected to geocentric orbits with perigees inside the Rocher limit. Material of the Earth mantle constitutes 1-2% of the total escaped mass and material of impactor cores (if impactors are differentiated) is from 0.5 to 2% of this mass. Estimated fragment sizes are from 10 cm to 10 m. Average velocities at infinity of escaped fragments are slightly higher than the velocities of impactors before they approach the Earth. These fragments, moving along heliocentric trajectories, intersect the Hill sphere of the Earth again in several hundreds of years on the average. Fragment trajectories cannot be noticeably changed by nongravitational forces (caused by Yarkovsky and Pointing-Robertson effects) during much longer time.

Large impactors carry the bulk of the mass accreted by the planet. We have obtained that the masses which escape the Earth gravity after large impacts are sufficient for formation of a Moon-sized satellite and potentially can be captured by the pre-lunar swarm just after impacts or when they return to the Earth again during their motion along heliocentric orbits. And we assume to consider the process of interaction of escaped material with the pre-lunar swarm of particles in the future.

Earth's minimoons

M. Granvik, *Department of Physics / University of Helsinki*, **R. Jedicke**, *Institute for Astronomy / University of Hawaii*, **and J.Vaubaillon**, *Paris Observatory*

It has recently been realized that the Earth is surrounded by a cloud of small moons (Granvik et al. 2012, Icarus 218, 262--277). These so-called minimoons are temporarily captured from the much larger population of near-Earth objects (NEOs). According to simulations accounting for gravitation only, a minimoon is typically captured for about nine months and it makes about three revolutions around the Earth during this period. The largest minimoon captured at any given time is about one meter in diameter but there are, e.g., 1000 minimoons larger than 10 centimeters in diameter orbiting the Earth at any given time. Larger objects are also captured but these captures occur less frequently. So far the only minimoon that has ever been detected is the few-meter diameter 2006 RH_{120}. The most likely explanations for the lack of minimoon discoveries are that (i) observers have not realized that they exist and erroneously categorized them as space debris and/or (ii) minimoons are too challenging to be detected and tracked with current survey telescopes due to their small size and rapid motion on the sky. Since existing (e.g., CSS and Pan-STARRS 1) and planned (e.g., LSST) survey systems constantly improve their detection capabilities, it is only a question of time when minimoons will start being detected in greater numbers. The scientific potential of minimoons is much larger than their small sizes might suggest and they open up several new possibilities in planetary science:

- An active laboratory for capture dynamics. The constant rate of minimoon captures (and releases) allows for the verification of theoretical and numerical results obtained for the temporary gravitational capture of moons in the context of the elliptic 4-body problem (Sun, Earth, Moon, minimoon).
- Population statistics for small asteroids. Minimoons provide a test of the NEO population statistics in a size range that is not well-sampled by contemporary asteroid surveys.
- Remote laboratory for detailed long-term studies of small asteroids. Small asteroids tend to be observable for a short time only. Their physical properties are therefore not typically well constrained by, e.g., photometric, polarimetric, and spectroscopic observations. Since minimoons spend months or even years orbiting the Earth there is ample time to carry out detailed observations of these objects.
- Laboratory analysis of an entire asteroid. Typical sample return missions bring back minute amounts of material and meteorite surfaces have been altered during the passage through the Earth's atmosphere and subsequent weathering. The extremely low requirement on the velocity change to get from the Earth to a minimoon combined with the relatively small minimoon diameters would allow an entire asteroid to be brought back to the Earth for laboratory analysis in a shielded spacecraft. Compared to meteorite studies and ordinary sample return missions this would open up completely new windows in several areas of asteroid research such as space weathering, interior structure, mineralogy, and maybe even astrobiology. The composition and structure of a minimoon would also set constraints on the origin and evolution of asteroids and, thus, on the evolution of the entire solar system.

Modeling the Collisional Origin of Satellites around Large KBOs

Z. Leinhardt, *School of Physics / University of Bristol*

In recent research we have developed an analytic description of the dynamical outcome for any collision between gravity-dominated bodies. In this model we have also derived scaling laws as a function of collision impact parameters that demarcate the transition between collision regimes such as cratering, perfect merging, partial accretion, partial erosion, hit-and-run, and catastrophic disruption. Using our new collision model we have found that the collision outcomes in the last stage of planet formation are diverse and span all possible collision regimes. From detailed numerical simulations we know that the majority of these collision outcomes can produce satellites of some form.

Of the four IAU recognized dwarf planets three have satellites: Pluto (4), Haumea (2), and Eris (1). All of the satellites around large KBOs are consistent with an impact origin. The collisional formation of both the Pluto-Charon and the Haumea systems have been studied in detail numerically. The Pluto-Charon system could be formed in a graze-and-capture event which fills a relatively narrow region of the impact collision-outcome parameter space squeezed between a merging and hit-and-run outcome. The Haumea system seems most easily formed by a slow but high angular momentum collision. In this case the satellites and collisional family are formed by rotational fission. The solution to this system again falls in a very specific and narrow region of the collision outcome parameter space just on the merging side of the merging/hit-and-run transition.

The significance of this work lies with its contribution to our understanding of the dynamical conditions necessary to produce specific collision outcomes. With additional observational data this will allow us to specify the original dynamical state of the Kuiper Belt placing strong constraints on the evolution of the rest of the solar system and possibly the formation of the Kuiper Belt objects themselves.

Formation of Pluto's small satellites

H. Levison, *Southwest Research Institute, Boulder*

The Pluto systems is one of extremes. In addition to Pluto, the system contains at least 4 satellites. Charon is the most massive, being more than 1/9 the mass of Pluto. This makes it the most massive satellite, relative to the primary, of any other planet or dwarf-planet in the Solar System. It orbits at 17 Pluto radii, which implies that the barycenter of the system is far outside the surface of Pluto. Recent analysis shows that its orbit is circular.

The other satellites are much smaller - having radii that are probably significantly less than 50 km. They are on nearly-circular, co-planer orbits. Perhaps one of their most intriguing characteristics is that they are all close to n:1 mean motion resonances (MMRs) with Charon. In particular, Nix, P4, and Hydra are close to the 4:1, 5:1, and 6:1 MMR, respectively. Observations are good enough for Nix and Hydra to conclude that while they are near their respective resonances, they do not appear to actually be librating in them.

It is generally believed that Charon formed in a grazing giant impact between two large Kuiper belt objects. If so, Charon probably formed on an eccentric orbit with a semi-major axis smaller than we see today and was pushed outward to its current location by tides with Pluto. The origin of the small satellites is significantly less clear due to the fact that they are far from Pluto, on nearly-circular orbits, and near the MMRs. It has been suggested that they were byproducts of the Charon-forming collision and were carried to their current orbits by the resonances as Charon migrated outward. However, recent analysis has shown that it is unlikely that this process would produce several objects on low-eccentricity orbits. Thus, the origin of these objects remain a mystery.

I will review the formation and evolution of Pluto's family of satellites. In addition, I will present some new work exploring a heretofore unexplored dynamical mechanism that might help explain the puzzling orbits of the small satellites.

Formation scenarios of asteroid binaries and implications for the science return of the MarcoPolo-R mission

P. Michel, *University of Nice / CNRS /Cote d'Azur Observatory*

Asteroids with satellites are observed throughout the Solar System, from subkilometre near-Earth asteroid pairs to systems of large and distant bodies in the Kuiper belt. The smallest and closest systems are found among the near-Earth and small inner main-belt asteroids. The MarcoPolo-R mission, which is currently in the assessment study phase of the M3-class mission at ESA, aims at returning a sample from such a binary near-earth asteroid of primitive class.

Small binary systems typically have rapidly rotating primaries and close secondaries on circular orbits. They also represent 15 percent of the near-Earth and inner main-belt asteroid populations. Several mechanisms have been proposed to explain their formation. Planetary fly-bys, if close enough, can cause the tidal break-up of a small body and result in the formation of a binary. However, the shape of the primary in this case, as shown by numerical simulations, is usually not consistent with the observed shape of binary primaries. Moreover, such tidal encounters are even more efficient at subsequently dissociating those binaries as a result of repeated planetary encounters. Therefore they cannot account for the high fraction of binaries. In the main belt, the catastrophic disruption of an asteroid can produce binary systems, but they do not match the observed properties of small binaries. It has been shown by numerical simulations that binaries can be produced by the slow spinup of a `rubble pile' asteroid by means of the thermal YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) effect. The properties of binaries produced by this mechanism match those currently observed in the small near-Earth and main-belt asteroid populations.

I will review the different formation mechanisms of binaries, and show that they have great implications in terms of the internal structure and surface geological evolution of the components. The binary asteroid (175706) 1996 FG3, baseline target of MarcoPolo-R, provides enhanced science return for a sample return mission. I will show that the choice of this target allows new investigations to be performed, enables investigations of the fascinating geology and geophysics of asteroids that are impossible at a single object, and can possibly offer a great advantage in terms of the sample science. Moreover, it allows testing of the formation scenarios of binaries, based on the properties of the primary that will be measured by the spacecraft.

Numerical Simulations of Small Solar System Binary Formation

D. Richardson, *University of Maryland at College Park,* **and P. Michel**, *University of Nice / CNRS /Cote d'Azur Observatory*

Binaries are found among virtually all small solar system binary populations, from near-Earth asteroids to the Kuiper belt. We present an overview of the present state of knowledge of these systems, with a focus on the near-Earth and inner main belt populations. Formation scenarios will be discussed, featuring numerical simulations of tidal and rotational disruption of gravitational aggregates. Since most scenarios require the progenitor body to be a rubble pile, we will also present evidence for the prevalence of such fragile objects among the small body population.

Why Mercury and Venus do not have a Moon?

J. Benkhoff and O. Witasse, *European Space Agency, ESTEC*

Earth has its moon and Mars possesses two tiny natural satellites, Phobos and Deimos. In addition all the outer planets have a very extensive system of natural satellites. However, most of them are very small, much smaller than our Earths moon. About half a dozen of them have comparable sizes to the Earth's moon: the four Galilean satellites Io, Europa, Ganymede and Calisto, Saturn's Titan, and Neptune's Triton. Saturn has an additional six mid-sized moons massive enough to have achieved hydrostatic equilibrium, and Uranus has five. It has been suggested that some satellites may potentially harbor life, however, this has not been confirmed or proofed so far.

Among all planets in our Solar System no moons have been discovered around Mercury and Venus. Thus the question is why Venus and Mercury do not have a natural satellite. It is also not known whether Venus or Mercury ever had a moon in their early stage of their evolution.

The accepted explanation for the origin of the Moon is a giant impact. Given current theories of Solar System formation, it is unlikely that Venus or Mercury would have avoided similar collisions. Simulations suggest that most large collisions create a disk from which a moon can forms [1].This paper reviews the current literature on the subject and attempts to give a possible answer to the question why Mercury and Venus do not have any satellites.

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Statistical co-accretion model of formation and composition of prelunar swarm

G. Pechernikova and V. Svetsov, *Institute for Dynamics of Geospheres RAS, Moskow, Russia*

Formation of near-planetary presatellite swarms is treated as a process accompanying the growth of planets. Early attempts to solve the problem of prelunar swarm origin in a framework of the co-accretion hypothesis have not been successful. Failures of these attempts, increasing comprehension of important role of large bodies in the planet accumulation, have drawn attention to the megaimpact hypothesis. A weak point of this hypothesis lays in the condition that the contributions of all but one largest object from the whole mass spectrum of preplanetary bodies should be considered negligible. And cosmochemical and geochemical consequences of both approaches are far from perfect.

We developed a statistical model of formation of the prelunar swarm in the context of the standard scenario of the formation of the Solar system. This model is based on the theory of accretion of mass and angular momentum by growing planets and takes into account the evolution of mass distribution of planetesimals. Inclusion of macroimpacts responsible for ejection of a small part (~ 0.01 of mass of accreated bodies) of material from the surface of the growing planet into heliocentric and geocentric orbits permits us to overcome the drawbacks of early approaches and to advance in the understanding of cosmochemical aspect of the problem. The extension of the theory of accumulation of mass and angular momentum to the case of a planet with a swarm makes possible to develop the theory of circumplanetary disk evolution.

The formation of more massive presatellite swarms is considered using a more complex model (than the co-accretion hypothesis), which includes additional mechanisms that enhance mass accumulation in the swarm. Apparently, the dominant mechanism is ejection of particles into geocentric and low-eccentricity heliocentric orbits by impacts of planetesimals on a growing planet, with subsequent partial capture of ejected material into the prelunar swarm. The mass of ejected particles can reach 0.1 of projectile masses (according to our 3D simulations of impacts). The ejections are distributed in a relatively narrow zone along the planetary orbit and are accumulated in the swarm. This mechanism can account for the relatively large mass of the satellite and the magnitude and distribution of angular momentum in the Earth-Moon system.

The mass fluxes in the model come from 5 reservoirs (the circumsolar swarm of planetesimals, the prelunar swarm of bodies, core and mantle reservoirs, as well as a reservoir modeling the primitive crust, which is enriched in Al-Ca silicate and is permanently created and destroyed by the impacts). Our calculations show a moderate depletion of a prelunar swarm in free iron (Fe-Ni-S content of less than 4-8% by mass) and enrichment in FeO (8-12%), aluminium oxide (4.5-6%) and CaO (3.7-5%), which depend on the extent of planet differentiation and the depth of impact mixing of the crust-mantle material. These results are consistent with the known models of Moon composition.

Impact craters: the evolutionary leaders

E.Martellato, *ESA/ESTEC***, L.Giacomini,** *University of Padova,* **B.Foing and J. Benkhoff,** *ESA/ESTEC*

Impact cratering is by far the most fundamental and widespread geologic process shaping the surfaces of solid bodies in the Solar System, and before it was even intimately associated with the formation and evolution of planets, satellites and small bodies. For instance, an early very large impact of Mars-sized object striking the differentiated proto-Earth has been proposed to be responsible for the origin of the Moon, whose surface was reshaped by a later, heavy bombardment.

On the other hand, the analysis of large and small-scale deformation features related to Lunar impact craters, including rings, rims, peaks, faults fractures and antipodal deformation structures, is essential for the understanding of impact tectonics, whose study is otherwise difficult on the few, heavily degraded or almost completely buried, Earth craters.

Craters are also of paramount importance to assess the mineralogical zoning of the upper hundred meters of the crust or even the composition of lunar mantle. In addition, the morphology of craters is also of great value for tectonic studies since craters readily record deformation processes and fault displacements; at the same time, studies of impact processes and Crater Size-Frequency Distributions can shed light on the rheology of the target itself (H&H 2007, Massironi 2009).

Last, but not the least, since impact craters population on a surface unit directly correlates with the time the unit was exposed to space, the cratering record is crucial for assessing the evolution of the impact flux, ages and even the thickness of geological units on planetary surfaces (Neukum 2001, Marchi 2009).

In this work, we would like to focus on the impact crater process and its role in the understanding of the evolution of our natural satellite.

Extra high underground temperature of oceanus procellarum revealed by Chang'e-1 lunar microwave radio meter data

W. Zhang, *University of Oxford*

Lunar soil temperature profile, including surface and interior, is an important parameter in lunar exploration. The lunar surface temperature has been measured by Diviner but the deep temperatures have only been measured at the Apollo 15 and 17 landing sites until the recent launch of the Chang'e-1 (CE-1) mission. The CE-1 Lunar orbiter is equipped with Microwave Radio Meter (MRM) instrument, which is a full-power 4 frequency microwave radiometer, and it is mainly used to detect the brightness temperature of lunar surface. The penetrating depth is generally less than 0.5 m at 37.0 GHz, 1.0 m at 19.35 GHz, and 2.0 m at 7.8 GHz, and the 3 GHz frequency channel can penetrate to a depth of 5 m or more [1]. Using data from this instrument we have successfully plotted the spatial variation of lunar surface temperature at 5 meter depth.

Studying the brightness temperature distribution data of lunar surface obtained by Chang'e-1, it ap-pears to closely follow the topographic information of the lunar surface. For example, in the 37.0 GHz brightness temperature map, we can distinguish the impact craters on the moon, while in the 3.0 GHz brightness temperature map we can distinguish mare and highlands. Thus we can link MRM temperature data with topography and geological features.

Through the comparison of the brightness tem-perature map and geological conditions on lunar surface, we can see an interesting phenomenon. In the Channel 4 and 3 brightness temperature maps, the Oceanus Procellarum (North 18.4, East 57.4), which is the largest of the lunar maria, shows nothing special. But if we look at Channel 1 (3.0GHz, 5m depth) brightness temperature map, which in-dicates deep underground temperature of the lunar surface, we instantly notice that the Oceanus Procel-larum has the highest underground temperature, and can thus be significantly noticed from the map. This means underground temperature is quite different with surface ones, as it is not expected to be influenced by solar radiation at these depths but by underground heat flow.

Oceanus Procellarum might be the possible location of the youngest basalts on the lunar near-side.The existence of this Procellarum basin is not completely accepted because the geochemical argu-ments for such a basin as well as the identification of ring structures of this basin are subject to alternative interpretation [3]. However, as we presented above, Chang'e-1 MRM data are consistent with a Procellarum basin. Since Procellarum basin concentrates more Thorium and FeO [2], there may be evidence for further melting and differentiation after the intial formation of the lunar crust (e.g. Glotch et al 2010), and may retain a higher sub-surface temperature, as thorium is a well-known magmatophile element.

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A possible reason why moon doesn't have a significant dipolar magnetic field

W. Zhang, *University of Oxford*

D'' layer's significance in the Earth's tectonics was just confirmed by Hirose and Lay in 2007 [1]. For half a century, few people foresee the significance of Core-Mantle Boundary (CMB) dynamics in the geosystem. As Lay et al [2] said on Nature, the CMB is about to replace the transition zone between Earth's upper and lower mantle as the region most likely to hold the key to a large number of geophysical problems. The story begins at the discovery of Post-perovskite (pPv) in 2004 [3], by Litaka and Hirose's group. Ppv is a high-pressure phase of magnesium silicate (MgSiO3). It is composed of the prime oxide constituents of the Earth's rocky mantle (MgO and SiO2), and its pressure and temperature for stability imply that it is likely to occur in portions of the lowermost few hundred km of Earth's mantle. The ppv phase has implications for the D" layer that influences the convective mixing in the mantle responsible for plate tectonics. And Postperovskite is much more effective in conducting heat. Later Ono and Oganov published two papers [4,5] predicting that ppv should have high electrical conductivity, perhaps 2 orders of magnitude higher than perovskite's conductivity.

At the Earth's infancy, there is no postperovskite, and the Earth's core is pure liquid, hence the magnetic field is very feeble. Later, when the Earth becomes colder, postperovskite formed, and accelerate the mantle convection, increase volcanic activities, expediate continental growth. Without postperovskite, the growth of the Earth's continent should be much slower, and volcanic activity would not be so active. Postperovskite strengthened the Earth's magnetic field, letting it prevent the cosmic ray from damaging the biosphere. As remarked by Thorne Lay [2], Mantle plumes from D'' layer could be very helpful to mantle convection. Lay's group detected that a hot mantle plume from CMB may be responsible for the volcanic island chain of Hawaii.

Now let us consider the situation on the Moon. The most successful model for explaining the lunar mantle siderophile element abundances requires a core of 5% of the mass of the Moon (500-km radius). According to calculation model in Diana et al [6], I estimate Moon has a temperature of at most 1700 K and a pressure of 40 KBar at its CMB. Therefore, sure because of the low pressure, perovskite cannot transform into post perovskite [7], hence can't form the post-perovskite layer. As a result it is impossible for moon to have a significant dipolar magnetic field.

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Modeling and measuring the mass distribution inside Phobos to constrain its origin

A.Rivoldini, P. Rosenblatt, S. Lemaistre, *Royal observatory of Belgium, Brussels, Belgium*

The origin of the Martian moons, Phobos and Deimos, is still an open issue. It has been proposed that they formed away from Mars and then captured by Mars gravitational attraction or that they formed in co-accretion with Mars or that they formed in-situ from a disk of debris in Mars' orbit. The capture scenario has, however, major difficulties to account for the current near-circular and near-equatorial orbit of Phobos. Previous works of tidal orbital evolution have shown the critical role of the tidal dissipation inside a satellite to make the capture possible, i.e. Phobos' interior might have high dissipative properties, which would be closer to those of icy material than to those of rocky material. Among the recent observations made by the Mars Express spacecraft, those concerning the internal structure of Phobos are particularly pertinent for assessing the scenario of origin. Indeed, the density of Phobos, 1.87 +/- 0.02 g/cm3, is lower than the density of presumed material analogs, suggesting that the interior of this small moon can contain light elements like porosity or water-ice. The former supports in-situ for-mation while the latter favorizes an asteroid capture scenario. Therefore, the assessment of the porosi-ty/water-ice content inside Phobos is a key measurement relevant to the open question about its origin.

In this study, we develop models of mass distribution inside Phobos, and use the measured libration of amplitude and density of Phobos to constrain the mass distribution within. We explore the possible internal mass distributions, considering three kinds of material inside Phobos: rock, porous-rock and water-ice. We compute the principal moments of inertia, related to the second-order gravity field coefficients, C20 and C22 and libration amplitude of Phobos, for each of these possible internal mass distributions. Then, we select the distributions that fit the measured libration of amplitude and the density of Phobos within their error bars. For those distributions, we find values of the gravity field coefficients which depart from the expected value of a homogeneous mass distribution for a large amount of porosity and a low amount of water-ice. In turn, precise measurements of both gravity field coefficients and rotation variations of Phobos may provide new constraints on the origin of this small moon of Mars.

A database of elongated craters on Mars to study the falling moonlet hypothesis

B. Buchenberger, *DLR,* **C. Popa,** *Osservatorio Astronomico di Capodimonte, Napoli,* **O. Witasse, D. Loizeau, A. Chicarro**, *Research and Scientific Support Department of ESA, ESTEC, Noordwijk, The Netherlands* **and P. Rosenblatt**, *Royal observatory of Belgium, Brussels, Belgium*

Elongated or elliptical craters on Mars have been analyzed since the 80's with the Viking catalogue of images [1,2,3]. They are formed by impacts with very shallow angle. An idea has been proposed that some of these craters may have been formed by tidal decay of the orbit of moonlets around Mars [1]. The motivation of this work is (1) to update the database of elongated craters using higher resolution, color and 3D images from Mars Express High Resolution Stereo Camera (HRSC); (2) to perform further tests for this moonlet hypothesis; (3) to give some constraints to some recent models of accretion disk around Mars [4,5], from which moonlets would have been formed and then would have fallen onto Mars.

This paper will provide with an overview of this new database. It contains up to almost 300 elongated craters which are divided into three main age groups according to their relative state of preservation. The database is composed of attributes like eccentricity, crater depth, terrain age, and orientation. Possible candidates for falling moonlets are discussed.

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Tidal displacements of Phobos' surface: A key information to reveal its origin.

S. Le Maistre (1), P. Rosenblatt (1), J. Castillo-Rogez (2), V. Dehant (1), and J.-C. Marty (3), N. Rambaux (4,5)
(1) Royal Observatory of Belgium, Brussels, Belgium, (2) Jet Propulsion Laboratory, Pasadena, USA, (3) CNES, Toulouse, France, (4) Universite Pierre et Marie Curie, Paris, France, (5) IMCCE, Observatoire de Paris, France
(SebastienLeMaistre@oma.be / Tel: +32-2-373-6755)

1. Introduction

Doppler measurements are used to compute the state vectors of a probe: orbiter around planets or moons or lander/rover at their surface. We propose here to use Direct-To-Earth (DTE) Doppler data from a lander at the surface of Phobos to measure the periodic variations in the moon's surface displacements due to the tides raised by Mars. We consider in this simulation a lander (fixed station located at the Phobos equator) tracked from the Earth during several weeks using a two-way radio signal in X-band (8.4 GHz).

In this paper we quantify the diurnal tidal displacement at the Phobos surface from a range of plausible values of Phobos tidal Love number h_2 and compare it with the precision that can be achieved on the determination of h_2.

2. Phobos tidal displacement

The tidal radial displacement (denoted here Δr) can be calculated from h_2 Love number through

$$\Delta r = h_2 \frac{V_t}{g}, \tag{1}$$

with the tidal potential V_t defined for a synchronous satellite as:

$$\frac{V_t}{g} = 3 \frac{M'}{M} \frac{R^4}{a^3} e, \tag{2}$$

where M' is the mass of Mars, M is the mass of Phobos, a is its semi-major axis and e its eccentricity.

By considering a broad parametric space that covers uniform elastic solid body to a rubble pile body, we find that h_2 ranges between 10^{-7} and 10^{-3}, leading to a position of the lander with respect to the center of mass of Phobos that could vary by up to 20 cm at the orbital period if Phobos is a rubble pile.

3. Phobos h_2 Love number estimate

The lander DTE measurements are sensitive to the surface displacements and could therefore be used to infer constraints on the ability of Phobos to deform in response to tidal forcing, a property expressed by the Love numbers h_2 and k_2.

We found that the precision on the determination of h_2 is below 10^{-3} in few days an reach a threshold at 10^{-5} after about one Earth year. The inferred precision on Δr is better than one centimeter after only 10 weeks, providing crucial information on the bulk rigidity, μ, of Phobos since h_2 is related to it through

$$h_2 = \frac{5}{2} \left(1 + \frac{19}{2} \frac{\mu}{\rho g R}\right)^{-1}. \tag{3}$$

4. Conclusions

This study shows that a lander mission will bring strong constraint on the geophysical properties of Phobos through the estimation of its tidal displacements from DTE measurements, revealing if Phobos is a rubble pile or not. This could give piece of answer to the crucial question of the presence or not of ice and/or porosity inside Phobos, given by the way valuable information about the physical processes prevailing at its origin.

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Deimos and Phobos compared observations by OMEGA/MEX

B.Gondet and J.-P. Bibring, *IAS Orsay, France*

The OMEGA imaging spectrometer on board the ESA/Mars Express mission has acquired hyperspectral images of both Phobos and Deimos. Given the distances of observations, Phobos is resolved down to a few hundreds of meter scale, while Deimos is essentiallty unresolved. Therefore, great care is to be taken when comparing the spectra. However, these two objects exhibit distinct spectral characteristics in the visible, which could offer clues as to their origin. Discussion with the pioneer observations by ISM and KRFM on board the Phobos 2 mission, and the recent CRISM/MRO will be proposed.

How to improve the orbit model of Phobos using observations with ALMA?

E. Villard, *ALMA/ESO*, **E. Fomalont**, *ALMA/NRAO*, **and O. Witasse**, *European Space Agency, ESTEC*

The fly-bys of Phobos by the Mars Express mission have provided the opportunity to observe the moon in detail, using all Mars Express instruments. The closer fly-bys (67 km on March 3, 2010) have analyzed the gravity field, by measuring the pull from Phobos. The gravity data analysis is however constrained by the precise knowledge of the position of Phobos. The need to improve this information has been clearly identified, in order to access to higher-order gravity field coefficients. The long-term evolution of Phobos would also be much improved with a better ephemeris.

The current best orbit model of Phobos, MAR085 - provided by JPL, has an estimated error that is greater than 1 km (Jacobson 2010), and this precision depends on the accuracy of the position measurements of Phobos. The error of the model also increases with time because of the uncertainty of the orbital period, increasing the position error along the orbital track (transverse error).

The Atacama Large Millimeter Array (ALMA) is a radio interferometer currently being built in the Chilean Atacama desert. With its high-altitude and very dry observing site, its frequency coverage down to the sub-millimeter and its long baselines (up to 17 km), ALMA will do precise astrometric observations (Lestrade 2008) to an accuracy <0.001”. These data will significantly improve the orbit models of many solar system objects.

Our first objective is to improve the knowledge of the orbit of Phobos by at least a factor 2. This can be achieved before completion of the project even with a maximum baseline length of a few kilometers. As more antennas are added and baseline lengths are extended, the sub-milliarcsec position of Phobos will be obtained. We will present an observing strategy to do so, taking into account the growing capacity of ALMA and the current knowledge on the orbit of Phobos.

Stratospheric Observatory for Infrared Astronomy Capabilities for Observations of Moons

M.Burgdorf, *Deutsches SOFIA Institut*, **and W. Reach**, *SOFIA Science Center*

The Stratospheric Observatory For Infrared Astronomy (SOFIA) is a joint US/German effort to fly a 2.5 meter telescope on a modified Boeing 747SP aircraft at stratospheric altitudes, where the atmosphere is largely transparent at infrared wavelengths. Key goals of the observatory include understanding the formation of stars and planets; the origin and evolution of the interstellar medium; the star formation history of galaxies; and planetary science. SOFIA offers the convenient accessibility of a ground-based observatory coupled with performance advantages of a space-based telescope. SOFIA's scientific instruments can be exchanged regularly for repairs, to accommodate changing scientific requirements, and to incorporate new technologies. SOFIA's portability will enable specialized observations of transient and location-specific events. Particularly relevant to this symposium is its ability to observe large moons directly, without saturation of the detectors or straylight from the planets – phenomena that affected many spaceborne observatories.

SOFIA's first generation instruments cover the spectral range of 0.3 to 240 microns and have been designed with planetary science in mind. The High-speed Imaging Photometer for Occultations (HIPO) is perfectly suited to measure occultations of stars by Solar System Objects, with SOFIA flying into the predicted shadows and characterizing the occulting object's atmosphere by means of a highly accurate light curve. The First Light Infrared Test Experiment CAMera (FLITECAM) offers imaging and moderate resolution spectroscopy at wavelengths between 1 and 5 microns that will be of use for the study especially of those moons, which have not been observed with NIMS on Galileo or VIMS on Cassini. The Faint Object infraRed CAmera for the Sofia Telescope (FORCAST) enables imaging and low-resolution spectroscopy at longer wavelengths than FLITECAM. It will, among other things, give access to the thermal emission of the Galilean satellites and shed light on their chemical composition and unique, radiation-induced reactions on the surface. By repeating the measurements from Voyager and the Infrared Space Observatory with better signal-to-noise ratio, vital information on the evolution of these moons can be gained. An instrument that will become available in the future is the Echelon cross Echelle Spectrograph (EXES). It will provide high-resolution spectral data between 5 and 28 microns that can for example be used to search for complex hydrocarbons and nitriles in Titan's stratosphere, benefiting from the lack of atmospheric interference by telluric water and carbon dioxide.

SOFIA's first light flight occurred in May, 2010, and the Cycle 1 observing program is scheduled to begin in August, 2012. The Program issued a call for new instrumentation proposals in the summer of 2011, and regular calls for observing proposals will be issued each autumn. SOFIA is expected to make some 120 science mission flights each year when fully operational in 2014.

Interaction of Phobos' surface with the solar wind and Martian environment

F. Cipriani, *ESA/ESTEC, Noordwijk, Netherlands*, **R. Modolo, F. Leblanc**, *LATMOS/IPSL/CNRS,* **and O. Witasse**, *ESA/ESTEC, Noordwijk, Netherlands*

Indirect evidence of a gas/dust tori along Phobos orbit has been inferred from data gathered during Viking orbiter and Phobos-2 missions (Ip et Banaszkiewicz 1990, Dubinin et al 1990), but never confirmed. Since Phobos' surface is directly exposed to the solar wind the structure and chemical nature of such tori would primarily depend on Phobos surface composition, which is in turn largely unknown, even though some proximity with D type asteroids can be inferred (Rivkin et al 2002).

We carried out 3D Monte Carlo simulation of the interaction of Phobos surface with the Solar Wind and Martian environment. The purpose of such simulations was to give information on the relative variability of the degassing rate of Phobos' surface along Phobos' orbit, based on different hypothesis on Phobos surface compositions (primitive carbon-rich or olivine rich), and describe the morphology of the cloud resulting from the ejection of neutral species along Phobos orbit.

We considered and compared the efficiency of a variety of degassing processes (solar wind ions and electrons sputtering, martian exospheric picked up ions sputtering, micrometeorites vaporization, photo-stimulated desorption) according to the region (solar wind, dayside/nightside, magnetosphere) crossed by Phobos around Mars.

SCF_LAB: an infrastructure to characterize laser altimetry of icy and rocky moons

S. Dell'Agnello, G. O. Delle Monache, M. Martini,C. Cantone, A. Boni,; S. Berardi, G.Patrizi, M. Maiello, C. Lops, and E. Ciocci, *Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati (LNF), Via Enrico Fermi 40, Frascati (Rome), 00044, Italy*

The SCF (Satellite/Lunar laser ranging Characterization Facility) and SCF-Test are a unique and unprecedented test facility and test procedure to characterize and model the detailed thermal behavior and optical performance of cube corner laser retroreflectors (CCRs) for Satellite/Lunar Laser Ranging (SLR/LLR) applications in accurately laboratory-simulated space conditions [1]. The SCF has been developed by INFN-LNF and is in use by NASA for the EarthÕs Moon, and by ESA and ASI for Galileo. The SCF modular, versatile and evolutionary design allows also for the laboratory characterization of Laser Altimetry (LA) investigations of moon SUrface SImulants (mSUSI), in place of CCRs. Laser altimetry has been and is an important tool in the exploration and planetary science of Mars (as shown by the past Mars Orbiter Laser Altimeter, MOLA, onboard the Mars Global Surveyor), Mercury (see the current Mercury Laser Altimeter, MLA, onboard MESSENGER) and the EarthÕs Moon (see the current Lunar Orbiter Laser Altimeter, LOLA, onboard the Lunar Reconnaissance Orbiter). The SCF is operated in an infrastructure owned by INFN-LNF, the SCF_LAB, which includes a dedicated clean room of class 10000 or better. Our key experimental innovation is the concurrent and integrated measurement and modelling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of CCRs/mSUSIs, under thermal conditions produced with a close-match solar simulator. The apparatus includes infrared cameras for non-invasive thermometry, CCR/mSUSI thermal control and real-time CCR/mSUSI movement to simulate satellite/mSUSI orientation with respect to solar illumination and laser interrogation beams. These capabilities provide unique pre-launch performance validation and a-posteriori characterization of as-built/in-flight performance of LLR/SLR/LA missions, including investigations in daylight conditions. To give a feeling of the novelty and effectiveness of the SCF, results of selected SCF-Test of CCRs are presented, including the SCF-Test of the first four Galileo In-Orbit Validation (IOV) satellites recently done for ESA. We are constantly upgrading the SCF_LAB. In fact, we are now procuring a vibration-insensitive Wavefront Fizeau laser Interferometer (WFI) to be used concurrently to CCR FFDP/temperature measurements, and a new close-match solar simulator (our second).

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A High Resolution Orbitrap Mass Spectrometer for future moon missions

R.Thissen, S.Cornelli, P. Puget, *Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), 38000 Grenoble, France,* **C. Briois, L. Thirkell, A. Boukrara, J.P. Lebreton**, *Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), UMR CNRS 7328, 3A Av. de la Recherche Scientifique, 45071, Orléans, France,* **H. Cottin, N. Grand**, *Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA), UMR CNRS 7583, université Paris Est Créteil et université Paris Diderot, Institut Pierre Simon Laplace, France,* **C. Szopa, N. Carrasco, A. Bouabdellah, C.Chapuis**, *Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS), UMR CNRS 8190, UPMC,UVSQ, 11 Bvd d'Alembert 78280 Guyancourt, France,* **C. Engrand**, *CSNSM, Univ. Paris Sud/CNRS, bat. 104, 91405 Orsay, France,* **A. Makarov**, *Thermo Fisher Scientific, Hanna-Kunath Str 11, 28199 Bremen, Germany*

Mass spectrometry, by its ability to analyse and quantify species from almost any type of sample (provided the appropriate sampling and ionizing method is used) is an excellent tool to study the complex mixtures, expected on the surface or in the atmosphere of moons and other airless bodies of the Solar System. The ability to assign univocally molecular formulae to masses requires high resolution mass analysers. The Orbitrap is a new concept of mass analyser that provides ultrahigh resolving power capabilities (M/ΔM beyond 100 000 up to m/z 400). It employs the trapping of pulsed ion beams in an electrostatic quadro-logarithmic field created between two barrel-shaped electrodes. Stable ion trajectories combine rotation around the central electrode with harmonic oscillations along it. These oscillations are detected using image current detection and are transformed into mass spectra using Fourier Transform. The lightweight, the absence of magnetic device, the very high resolution and good sensitivity of this mass spectrometer make it very attractive for space exploration.

In the frame of Jovian moons exploration by ESA's mission JUICE we study a space version of the Orbitrap acting as mass analyser for a dust detector in the vicinity of Jupiter's moons Europa, Ganymede and Callisto. The concept relies on the collection (at kilometric speeds) of micrometer size particles ejected from the surface of the moons (1).Their chemical analysis obtained by mass spectrometry provides key information concerning the origin and evolution of the surface of the bodies: presence of organics, salts, isotopic fractionation, etc. High mass resolution will strengthen elemental analysis of the materials, as well as provide important in situ information for the complementary spectroscopic analysis.

In the frame of Marco Polo sample return mission, we study the ILMA instrument (2). This lander oriented, small size instrument, produces ions by laser desorption/ionization and detects them with the Orbitrap analyser. The objective would be to characterize in situ the surface of a Near Earth Asteroid. The same technique would be applicable to any airless body lander (examples are: Europa lander studied by US, Ganymede lander studied by Russia, Enceladus lander). These in-situ high resolution measurements would bring definitive answers concerning the elemental and molecular composition of the surfaces of small bodies, and the ability to ablate material (by few micrometers) would as well give access to pristine or at least less weathered material.

On Titan, Cassini-Huygens observed large molecular structures in the atmosphere, and on the surface. We do not know most of the molecules, but they contain C, H and N. The presence of cyclic molecules, amines, hydrocarbons, and potentially oxygen suggests that molecules similar to biological building blocks on Earth could be formed. Titan is potentially in a phase of pre-biotic evolution. As stated in previous future Titan mission studies, including in the TSSM one, a high resolution mass spectrometer will be a key instrument for a future mission.

The Orbitrap mass analyser concept was demonstrated in 2000 (3). It is now used in many commercial high resolution mass spectrometers. A space version of an Orbitrap mass spectrometer is currently under development among a consortium of 4 French laboratories: IPAG, LPC2E, LATMOS, LISA, in close collaboration with ThermoFisherScientific. A laboratory prototype is now operational in LPC2E, Orleans; it is being used to assess the performance requirements, define and validate the specifications of a space instrument. We will describe the Orbitrap concept, its performances, and the required steps to develop an Orbitrap high resolution mass spectrometer that would meet the required performances for future Solar System moon and other airless bodies missions.

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A New Numerical Model for multiple systems : ODIN

L.Beauvalet, V.Lainey, and F. Marchis, *IMCCE-Observatoire de Paris*

The fitting of a numerical model to observations is a very efficient way to have access to physical parameters in the case of multiple systems. We describe our numerical model developped especially for multiple systems : ODIN (Orbite, Dynamique et Integration Numerique). This model is based on the integration of N-objects motion in a barycentric reference frame. Our model includes the integration of orbital motion's variationnal equations, a key feature for least-square method fitting. We present the results obtained when fitting this model to observations of Sylvia and Eugenia, two triple systems of the Main Belt. We also discuss the possible implications of our results on those asteroids'structure based on the difference between the theoretical value of their polar oblateness J2 and the value obtained from the fitting.

Charged Nanograins in the Plume of Enceladus

G.H. Jones, A.J. Coates, *Mullard Space Science Laboratory, University College London, UK,* **and F. J. Crary,** *Southwest Research Institute, San Antonio*

In 2005, it was discovered as a result of anomalous magnetic field observations by the Cassini spacecraft, that Saturn’s 504 km-wide moon Enceladus is active. Detailed observations of the moon by the spacecraft have revealed its south polar region to be actively expelling large quantities of gas and water ice grains. This ejection of material forms a plume extending southwards from the moon, within which are discrete jets emanating from surface fissures. Cassini has traversed this plume several times since 2005. The spacecraft’s Cassini Plasma Spectrometer, CAPS, was designed to detect thermal plasma in Saturn’s magnetosphere (Young et al. 2004). However, when aligned with the direction of motion, the instrument’s different sensors have proven to be capable of directly detecting charged icy grains within the plume measuring up to several nm in size, if we assume a single electron charge on the particles (Jones et al. 2009, Hill et al. 2012). We present an overview of recent observations of these charged nanograins, and our inferences regarding their spatial distribution within the plume. We also review information about the subsurface conditions at Enceladus that the characteristics of this population of small icy grains can provide.

The origin and evolution of Titan's atmosphere

Athena Coustenis, *LESIA / Paris-Meudon Observatory / 5, place Jules Janssen, 92195 Meudon Cedex, FRANCE*

Titan is the only icy satellite with a dense atmosphere comparable in many ways to that of the Earth's atmosphere. Titan's atmosphere prevents the surface from direct interaction with the plasma environment, but gives rise to Earth-like exchanges of energy, matter and momentum. Titan's atmosphere and surface present many similarities with the Earth, harbouring a dense dinitrogen (98%) atmosphere, rich in methane (1.4%) and other organics in combination with a diverse surface curved by terrestrial-like features. The exact origin of the atmospheric mother molecules and the surface composition remain largely a mystery today.

Following the Voyager flyby in 1980, Titan was intensely studied from the ground-based large telescopes (such as the VLT) and by artificial satellites (such as ISO) for the past three decades [1-4]. Prior to Cassini-Huygens, Titan's atmospheric composition and thermal structure was known to us from the Voyager missions and also through the ISO observations which have provided the first detection of the water vapor and benzene in Titan's atmosphere and given a precise measure of the chemical composition as a disk-average. Since then, our perception of Titan has greatly been enhanced thanks to Cassini-Huygens instruments like CIRS [4,5], VIMS, INMS [7], ISS, HASI, or DISR [6], but many questions remain as to the nature of the haze surrounding the satellite, the complex organic chemistry discovered in the upper atmosphere and the composition of the surface, strongly interacting with the lower atmosphere.

In 2010 a whole Saturnian year has been completed since the Voyager visit on 1980. By comparing all the available space data pertaining to the neutral atmosphere of Titan (Cassini/CIRS, Voyager/IRIS and ISO/SWS essentially), we can therefore look for temporal variations of its temperature and composition [4]. These spectra are analysed by using a radiative transfer code [1] and then compared also with ground- and/or space- based acquisitions. We then also compare these results with other inferences from the Voyager missions [1] and other ground/space –based observations [2-3] to obtain information as to the interannual variations and seasonal effects on Titan. Studying Titan's organic budget by the Cassini-Huygens instrumentation will enable scientists not only to understand the origin, evolution and dynamics of its atmosphere, but also to investigate its astrobiological potential.

I will discuss our current understanding of Titan's complex atmospheric environment in view of recent findings [4], with emphasis on the atmospheric structure (temperature and composition) and the possible origin of the atmospheric constituents [8]. I will discuss how these and other elements can give us clues as to the origin and evolution of the satellite.

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Io: A (geo-)physicist's playground

N.Thomas, *Space Research and Planetology Division, University of Bern*

With the focus on water and habitability, and the severe radiation environment near-by, the Jovian satellite, Io, has been slightly neglected in recent years. However, the physical processes which occur at Io are highly unusual and may help us understand satellite formation in the presence of a large primary.

The almost complete absence of water and the Laplace resonance place constraints on the formation and early evolution of the Jovian satellite system as a whole and Io in particular. The subsequent surface evolution has been driven by tidal heating which has led to extensive volcanism and, indirectly, to substantial mass loss through the interaction with the Jovian magnetosphere. The composition of the material lost, that remaining in the tenuous atmosphere and on the surface, and that of the volcanic plumes suggests that a detailed inventory of the internal liquid layer can be derived through remote and in situ measurement. Furthermore, some works suggest the physical processes currently seen at Io (e.g. tidal heating, mass loss) may have been present at a very early stage of the development of the system (although there is evidence to the contrary).

We look here at the importance of Io in studies of the Jovian system and show that mission concepts, such as the Io Volcano Observer, offer the possibility of an investigation of one of nature's remarkable objects.

Satellite-Magnetosphere Interactions

G.H. Jones, *Mullard Space Science Laboratory, University College London, UK*

Many moons in our solar system follow orbits either partially or completely within their parent planet's magnetosphere, thus in some cases encountering radially different plasma environments to those to which they'd be exposed in the solar wind. Earth's moon regularly crosses the terrestrial magnetosphere's magnetotail, but it is at the moons of the giant planets Jupiter and Saturn that the strongest interactions between magnetospheres and moons have been observed. In situ observations by spacecraft such as Galileo and Cassini have revealed a diverse range of such interactions at these planets' satellites. The exposure of moons to incident magnetospheric plasma drives surface processes such as radiolysis, controls surface charging, and leads to the generation of sputter-induced atmospheres. Some moons such as Io and Enceladus have significant exospheres and ionospheres fed by internal processes. The ionization of gaseous species provides a significant source of pickup ions within the host magnetosphere, and the plasma near several moons has been found to be coupled to the parent planet's ionosphere, creating auroral footprints at both Jupiter and Saturn. A full understanding of the processes involved in the acceleration of particles to form these footprints is still forthcoming. An overview will be given of all these processes, and those that occur at the unique cases of Ganymede: a moon largely shielded from the Jovian magnetosphere by its own magnetic field, and Titan, with a dense atmosphere orbiting in Saturn's outer magnetosphere.

Plasma interactions at Titan and icy moons: evolving ionospheres

A.J. Coates. A. Wellbrock, G.H.Jones, *Mullard Space Science Laboratory, University College London, UK,* **F. Crary, D.T.Young,** *Southwest Research Institute, USA,* **M.Thomsen,** *Los Alamos National Laboratory, USA***, D.Reisenfeld,** *University of Montana, USA*, **R.E.Johnson,** *University of Virginia, USA***, T.E.Hill**, *Rice University, USA*

Cassini has revealed a wealth of new information about Saturn's satellites. Here, we focus on Titan but also consider Enceladus. At Titan, large negative and positive ions are observed during Cassini's close flybys, and the composition evolves with the largest ions seen at the lowest altitudes. In addition, plasma escapes from Titan as seen during tail flybys, causing an evolution of the atmosphere and ionosphere over time. At Enceladus, the evolution is over distance, with cluster ions and charged dust grains seen in the plume ionosphere. At Rhea and Dione, production and loss of particles due to energetic particle bombardment controls the weak atmospheres. We consider the evidence for, and the effects of, ionospheric evolution at these important objects.

Surface radiation environment of Saturn’s icy moon Mimas

T. Nordheim, *Mullard Space Science Laboratory - University College London***,**
K. Hand, *Jet Propulsion Laboratory California / Institute of Technology***,**
C. Paranicas, *Applied Physics Laboratory / Johns Hopkins University***, P. Kollmann,** *Max Planck Institut fuer Sonnensystemforschung***, G. Jones, A. Coates,** *Mullard Space Science Laboratory - University College London***, N. Krupp,** *Max Planck Institut fuer Sonnensystemforschung*

A significant portion of moons in our Solar System are embedded within a planetary magnetosphere, such as is the case for many of the moons of the giant planets Jupiter, Saturn, Uranus and Neptune. The inner regions of these magnetospheric environments are characterized by populations of trapped charged particles, from thermal plasma to high energy energetic ions and electrons. Moons orbiting within these magnetospheres are therefore often subject to continuous bombardment by multiple particle species over a wide range of energies. It is known that such bombardment may induce chemical alterations within icy surfaces through the process of radiolysis, an effect which has the potential to significantly change surface and near-surface composition over typical geological timescales. In order to make quantifiable predictions on the surface composition of these moons, it is therefore critical to have a detailed measure of deposited dose into the surface from the relevant magnetospheric particle species. We will present dose-depth profiles for the near-surface of Saturn’s innermost large moon Mimas. This has been computed using a Monte Carlo particle transport code with representative energetic electron and proton spectra derived from measurements made by the MIMI-LEMMS particle instrument on the Cassini spacecraft.

Magnetospheric Ion Implantation in the Icy Moons of Giant Planets

G. Strazzulla, *INAF-Osservatorio Astrofisico, Via s. Sofia 78, 95123 Catania, Italy*

Solid surfaces of the icy moons of giant planets are continuously modified by ion implantation of energetic ions and electrons from planetary magnetospheres. The study of the induced effects has been based on laboratory simulations aimed e.g. at investigating the induced non-thermal chemical reactions that lead to the formation of a large number of molecules, not present in the original target. Frozen layers made of simple molecules, pure (e.g. H_2O, NH_3, CO_2, SO_2 and many others) or mixtures are deposited at low temperature (10-150 K) and irradiated with the chosen ion beam at different fluences. If the thickness of the target is greater than the ion penetration depth, the ions are implanted in the target. Implanted reactive ions (e.g., H^+, Cn^+, Nn^+, On^+, Sn^+) induce all of the effects of any other ion, but in addition have a chance, being stopped in the target, to form new species containing the projectile. These experiments are of fundamental relevance to clarify the formation history of the molecular species in particular to reveal their endogenic or exogenic origin. Some of the results obtained so far will in my laboratory will be discussed, in particular: (1) H_2O_2 is formed by ion bombardment of pure water ice and such a process is believed to be responsible for its presence in the ices of Europa and other satellites. (2) The experimental results relative to implantation of reactive ions indicate that some molecular species observed on icy planetary surfaces (e.g. CO_2 and hydrated sulfuric acid) could have been formed by implantation of reactive ions that populate the jovian (and others) magnetosphere and continuously bombard the surfaces of the embedded satellites. (3) Specific predictions can be done on the relationship between the fluxes of reactive ions and the formation of species on spatially resolved regions on the surface of Europa. This is of the greatest relevance to understand existing data from space missions and to program future observations.

Ridge formation and de-spinning of Iapetus via an impact-generated satellite

K.J. Walsh, H.F. Levison, A.C. Barr, L. Dones, *Southwest Research Institute, Boulder*

We present a scenario that both builds the equatorial ridge and despins Iapetus through an impact-generated disk and satellite. This impact puts debris into orbit, forming a ring inside the Roche limit and a satellite outside. This satellite rapidly pushes the ring material down to the surface of Iapetus, and then itself tidally evolves outward, thereby despinning Iapetus.

Evaluation of this scenarios requires several steps starting with the assumption that a sub-satellite forms around Iapetus from an impact-generated disk of debris. We first find the maximum semi-major axis a sub-satellite could have before being stripped by Iapetus. We then use this maximum separation in tidal evolution integrations to estimate a mass range for sub-satellites that can expedite the de-spinning of Iapetus.

This scenario can despin Iapetus an order of magnitude faster than when tides due to Saturn act alone. Eventually, the satellite is stripped from its orbit by Saturn. The range of satellite and impactor masses required is compatible with the estimated impact history of Iapetus.

Depth of Enceladus craters: implications of surface properties on the early differentiation of icy moons

K. Degiorgio, S. Rodriguez, C. Ferrari, and A. Brahic, *University Paris-Diderot Paris 7 / CEA Saclay*

We conduct an extensive analysis of the Cassini/ISS observations of Enceladus old terrains with the help of a model that can simulate the photometric behavior of a cratered plain and its regolith. This model adapted from the crater roughness model of Buratti and Veverka [1985] allows to retrieve the aspect ratio of a crater and the physical properties of its regolith within a robust and fast scheme of inversion of a set of images presenting a sufficient variety in viewing geometries, independently of their spatial resolution. Our study includes 29 craters equally distributed over Enceladus\textquoteright{}s cratered regions. The regolith's properties and the craters depth-to-diameter ratios that we derive do not show regional heterogeneity. By putting together all the measurement of the craters depth, a new constraint is given, on the value for Enceladus transition diameter, found to be 17.8±5.5km. The effective viscosity and the cohesion of Enceladus crust material, deduced from the value of the transition diameter, are 1.2±0.5 .108 Pa.s and 89±18 kPa respectively. All these clearly indicate that at the time of craterisation, Enceladus cratered terrains had ground properties similar to most of the icy moons of Jupiter, Saturn and Uranus. This suggests that most of these bodies were already partially differentiated at the early stage of craterization. Moreover, this may indicate that, since its formation, Enceladus geological activity has never spread out of the actual fractured regions about the south pole.

Mimas and Enceladus: Formation and interior structure from astrometric reduction of Cassini images

R. Tajeddine, V.Lainey, N. Rambaux, *IMCCE / Observatoire de Paris,* **N. Cooper**, *School of Mathematical Sciences Queen Mary University of London,*
S. Charnoz, *CEA Saclay*, **C. D.Murray**, *School of Mathematical Sciences Queen Mary University of London*

The origin and evolution of the Saturnian satellites is still debated. While the canonical formation model creates many main moons in Saturn's subnebulae, a new model suggests a possible formation at the outer edge of a past massive ring (Charnoz et al. 2011). Furthermore, many interior structure models were suggested for Enceladus in order to explain the geysers observed in its South polar region. For instance, Nimmo and Pappalardo (2006) suggest the existence of a low density anomaly in the ice crust, and Collins and Goodman (2007) explain these geysers by an internal local "sea" with higher density than the ice crust. It is also noteworthy that in the model of Charnoz et al. (2011), the core of the satellites is not necessarily symmetric, due to the accretion of icy material onto large silicate chunks (> 10 - 100 Km).

All these previous models may result in a shift between the center of mass and the center of figure of the satellites. We used the astrometry of Cassini ISS NAC images of Mimas and Enceladus to attempt to quantify such a shift considering, on one hand, the satellite's observed position as the center of figure and, on the other hand, its predicted position from the orbital ephemeris as the center of mass. In studying such a shift, we may add new constraints to the existing models and possibly discriminate between the various interior and formation models of the Saturnian system.

Constraints on Moon evolution and planetary processes using SMART-1 data

B.H. Foing, *European Space Agency (ESA), The Netherlands & Vrije Universiteit, Amsterdam*

SMART-1 demonstrated the use of Solar Electric Propulsion, tested new technologies for spacecraft and instruments miniaturisation, and provided an opportunity for science [1-12]. The SMART-1 spacecraft operated on a science orbit for 18 months until impact on 3 September 2006. To date, 68 refereed papers and more than 300 conference or technical papers have been published based on SMART-1 (see ADS on SMART-1 scitech website). SMART-1 data are accessible at ESA Planetary Science Archive PSA [13].

We review SMART-1 results that are relevant to the studies of planetary processes during lunar evolution (cratering impacts, bombardment chronology, volcanism, tectonics and surface space weathering) [8,9,12] . SMART-1 results are relevant to the study of properties of the lunar dust, with multi-angular photometry of Mare and specific regions to diagnose the regolith roughness and to constrain models of light reflection and scattering [14] that can be extended to understand the surface of other moons and asteroids. That is relevant to the study of lunar dust.

SMART-1 studied impact craters and ejecta (including from the SMART-1 impact itself) [12, 15]. The SMART-1 archive observations have been used tin conjunction with data from Kaguya, Chandrayaan-1, Chang'E 1, the US Lunar Reconnaissance Orbiter, the LCROSS impact, and upcoming missions. SMART-1 data were also used for studies of potential sites relevant to future exploration [12, 16, 17, 18].

Acknowledgements and References: We thank members of SMART-1 Science and Technology Working Team (STWT) and collaborators for their contribution. SMART-1 Scitech website: sci.esa.int/smart-1 and SMART-1 Public website: www.esa.int/smart-1

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Mars Express investigations of Phobos

O. Witasse, *ESA/ESTEC***, T. Duxbury,** *School of Physics, Astronomy and Computational Sciences /George Mason University***, *and all Mars Express teams***

The European Mars Express spacecraft orbits the red planet for more than 8 years. The teams have made outstanding discoveries in many scientific fields from which a new view of Mars emerges. In the last few years, the Phobos moon also became a major goal of the mission. Thanks to the polar and elliptical orbit, regular flybys of Phobos occur every five months, allowing unique observations and measurements to be made. A unique series of flybys was executed in February- March 2010, with the closest approach of 62 km from the surface on 3 March 2010. A selection of results from the Mars Express investigations at Phobos is given below:

- The moon ephemerids have been significantly improved by combining Mars Express images and radio-tracking data;
- The most precise determination of the mass value has been performed, and an estimation of the gravity coefficient ‘J2’ provides some constraints on the internal structure;
- Unique radar echoes have been acquired by the MARSIS radar;
- Regarding surface studies: the highest resolution images have been acquired. Variations of surface temperature are computed; new information on surface composition is provided by OMEGA, PFS and SPICAM, using a unique dataset covering the ultraviolet, visible and infrared range;
- Ion measurements have shown that solar wind protons are strongly backscattered from Phobos. Since the Moon of the Earth also backscatters the solar wind protons similarly, the backscattering of the solar wind protons is a common feature of the regolith in space, in contrarily from the classical argument that the regolith is a complete absorber of the solar wind protons;
- The Mars Express results allow revisiting the question of Phobos’ origin. The scenario in which the Martian moons result from the re-accretion of material is now favored.

This paper will give an overview of the executed flybys, operational challenged and science highlights.

The origin of the Martian moons revisited

P. Rosenblatt, *Royal Observatory of Belgium, Brussels*

The origin of the Martian moons, Phobos and Deimos, is still an open issue: either they are asteroids captured by Mars or they formed in-situ from a circum-Mars debris disk. The capture scenario mainly relies on the remote-sensing observations of their surface, which suggest that moon material is similar to outer-belt asteroid material. This scenario, however, requires high tidal dissipation rates inside the moons to account for their current orbits around Mars. Although the in-situ formation scenarios have not been studied in great details, no observational constraints argue against them. Low attention has been paid to the internal structure of the moons, while it has a pertinent importance for their origin. The low density of the moons indicates that their interior contains significant amounts of porosity and/or water ice. The porosity content is estimated in the range of 30-60% of the volume for both moons. This high porosity enhances the tidal dissipation rate but not sufficiently to meet the requirement of the capture scenario. On the other hand, a large porosity is a natural consequence of re-accretion of debris in Mars' orbit, thus providing support to the in-situ formation scenarios. The low density also allows abundant water ice inside the moons, which might significantly increase the tidal dissipation rate in their interiors, possibly to a sufficient level for the capture scenario. Precise measurements of the rotation and gravity field of the moons are needed to tightly constrain their internal structure in order to help answering the question of the origin.

Meteorite Analogs for Phobos and Deimos: Unraveling the origin of the Martian moons

P. Vernazza, *ESO Garching, Germany***, O.Witasse, F. Cipriani,** *ESA/ESTEC*

The origin of the Martian moons has not been solved yet and is one of the most intriguing puzzles of the inner solar system. The three proposed scenarios for the origin of the moons are the following: 1) Capture of two distinct outer main belt asteroids 2) Formation in place (The Moons accreted in their present position) 3) Origin as Mars impact ejecta. Dynamicists argue that the present orbits of Phobos and Deimos could not be produced following capture, and so they must have originated near Mars at 1.5 AU, where the satellites are found today. However, every observable physical property (albedo, VNIR reflectance ...) indicates that the Martian satellites once resided in the outer belt (~3 AU), suggesting the objects must be captured [1]. Providing new constraints on the composition of the moons would bring us very close to the solution of this long standing issue.

Phobos and Deimos share similar visible-near infrared (0.4-2.5 µm) spectra suggesting that they have a similar surface composition. However, it appears that Deimos' spectrum is redder than any Phobos' spectrum. Further, a strong color difference is observed on Phobos itself: the spectrum covering the bright crater Stickney is much bluer than any spectrum scanning other regions of Phobos. Can these color differences be explained by space weathering [e.g., 2, 3]? Or is a variation of the surface composition the cause of the observed slope differences?

We found two meteorites, Tagish Lake and WIS 91600, whose spectra match PhobosÕ blue spectrum (crater Stickney) but not Phobos' redder spectra, nor Deimos spectrum. We plan to test if space weathering processes are the cause of the strong color difference observed between Phobos' blue region (crater Stickney) and other parts of Phobos and Deimos. Said differently, we plan to test if space weathering processes can redden and darken the initially WIS 91600- or Tagish Lake-like spectrum of a fresh Phobos surface (Phobos blue; supposing the latter surface is fresh), transforming its appearance to that of a Phobos red or a Deimos spectrum. If not, this would imply that both meteorites differ in composition from the martian moons.

To test this hypothesis, we started reproducing in the laboratory the effects of the solar wind ion irradiation on both meteorites. Such experiments were conducted at the Observatory of Catania (Italy) and at the University of Virginia (USA). Furthermore, a modal analysis of WIS 91600 was conducted at NHM, London (UK) in the same way as previously done for Tagish Lake [4]. We will present the results of these experiments and their immediate implications.

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Future plans for Cassini

N. Altobelli, *ESA/ESAC, Villanueva de la Cañada, Spain*

The Cassini mission will be touring the Saturnian System until 2017. We present an overview of the upcoming science operations focused on the exploration of Saturn's moons. As Cassini is going to fly highly inclined orbits in the coming years, there will be significantly less close icy moons encounters compared to the past two years, until the next Dione, Tethys and Enceladus flybys in 2014-2015. In contrast, Titan will be targeted regularly until 2017.

JUICE: an ESA L-mission to the Jupiter system

M.K. Dougherty, *Imperial College, UK***, O.Grasset,** *Nantes Univ., France***, D. Titov, C. Erd**, *ESA/ESTEC, Netherlands***, E. Bunce,** *Leicester Univ., UK***, A. Coustenis,** *Paris-Meudon Observatory***,** *France,* **M. Blanc,** *Ec. Polytechnique, France***, A. Coates,** *Univ. College London, UK,* **P. Drossart,** *Paris-Meudon Observatory***, L. Fletcher,** *Oxford Univ., UK***, T. van Hoolst,** *Roy. Obs. of Belgium, Belgium***, H. Hussmann, R. Jaumann,** *D.L.R., Germany***, N. Krupp,** *M.P.S., Germany***, O. Prieto-Ballesteros,** *INTA-CSIC***, P. Tortora,** *Univ. of Bologna***, F. Tosi,** *Inst. for Space Astrophys. and Planetology, Italy* **and A. Wielders,** *ESA/ESTEC, Netherlands*

JUICE (JUpiter ICy moon Explorer) is an L-class mission candidate in the ESA's Cosmic Vision programme 2015-2025. JUICE is a European-led mission that would perform detailed investigations of Jupiter and its system in all their inter-relations and complexity with particular emphasis on Ganymede as a planetary body and potential habitat. Investigations of Europa and Callisto would complete a comparative picture of the Galilean moons. By performing detailed investigations of Jupiter's system in all its complexity, JUICE would address in depth two key questions of ESA's Cosmic Vision programme: (1) What are the conditions for planet formation and the emergence of life? and (2) How does the Solar System work?

The overarching theme for JUICE has been formulated as: The emergence of habitable worlds around gas giants. The main science objectives for Ganymede are: characterisation of the ocean layers; topographical, geological and compositional mapping of the surface; study of the physical properties of the icy crusts; characterisation of the internal mass distribution, investigation of the exosphere; study of the Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere. For Europa, the focus would be on the non-ice chemistry, understanding the formation of surface features and subsurface sounding of the icy crust over recently active regions.
JUICE would perform a comprehensive investigation of the Jupiter system as an archetype for gas giants. The circulation, meteorology, chemistry and structure of Jupiter would be studied from the cloud tops to the thermosphere. The focus in Jupiter's magnetosphere would include an investigation of the three dimensional properties of the magnetodisc and in-depth study of the coupling processes within the magnetosphere, ionosphere and thermosphere. Aurora and radio emissions and their response to the solar wind would be elucidated. Within Jupiter's satellite system, JUICE would study the moons' interactions with the magnetosphere, gravitational coupling and long-term tidal evolution of the Galilean satellites.

The JUICE spacecraft would be launched in June 2022 by Ariane 5. After the orbit insertion in January 2030 the spacecraft would perform a 2.5 year tour in the Jovian system focusing on observations of Jupiter's atmosphere and magnetosphere. During the tour, gravity assists at Callisto would shape the trajectory to perform two targeted Europa flybys and raise the orbit inclination up to 30°. 13 Callisto flybys would enable unique remote observations of the moon and in situ measurements in its vicinity. The mission would culminate in a dedicated 8 months orbital tour around Ganymede.

JUICE would be a three-axis stabilised spacecraft with dry mass of about 1800 kg at launch, chemical propulsion system and 60-75 m2 solar arrays. The high-gain antenna of about 3 m in diameter would provide a downlink capability of not less than 1.4 Gb/day. Special measures would be used to protect the spacecraft and payload from the harsh radiation environment at Jupiter. The spacecraft would carry a highly capable state-of-the-art scientific payload. The model payload consists of 11 instruments with total mass of ~104 kg. The model remote sensing package includes spectro-imaging capabilities from the ultraviolet to the near-infrared, wide angle and narrow angle cameras and a submillimetre wave instrument. The model geophysical suite consists of a laser altimeter and a radar sounder, complemented by a radio science experiment. The model in situ package comprises a magnetometer, radio and plasma wave instrument, including electric fields sensors and a Langmuir probe, and a powerful particle package.

Science and payload activities in support of the ESA Lunar Lander

J.D. Carpenter, R. Fisackerly, A. Pradier, B. Houdou, D. De Rosa, B. Gardini,
ESA-ESTEC, Keplerlaan 1, 2201AZ, Noordwijk, The Netherlands

ESA's Human Space Flight and Operations directorate is continuing with preparations for its Lunar Lander project. The Lunar Lander is an unmanned precursor mission to future human exploration, whose purpose is to drive the development of key technologies and generate scientific knowledge that will position Europe as a participant in future exploration of the Moon and beyond. The primary objective of the mission is to demonstrate soft precision landing with hazard avoidance. Once on the surface the mission provides an opportunity for the operation of a scientific payload which addresses the major unknowns for future exploration activities. The mission targets a landing site close to the Lunar south pole in order to demonstrate precision landing and to make use of the favorable illumination available at key locations in this region. The mission has been studied at Phase B1 level with Astrium (Bremen) as the prime contractor, since August 2010.

Scientific topics for investigation: The scientific topics that have been defined for the mission emphasise areas which will be of importance for the future of exploration but where significant unknowns remain. These include the integrated dusty plasma environment at the surface of the Moon and its effects on systems [e.g. 2]; lunar dust as a potential hazard to systems and human explorers [e.g. 3]; potential resources which can be utilized in the future including both volatiles (e.g. water) and those derived from minerals; and radiation as a potential hazard for human activities. Each of these topics is supported by an independent science Topical Team. These Topical Teams continuously review the science requirements and activities of the mission in the wider context of research into a scientific topic including other space platforms and research in terrestrial laboratories.

Model payload: In order to address these scientific topics and meet the associated requirements a model payload has been defined. This model payload is used to inform the mission study in advance of a formal selection in order to ensure that challenges associated with accommodating candidate experiments are properly accounted for. In addition the model payload provides a reference point for further investigations into optimal ways to address unknowns associated with the identified scientific topics. The model payload includes a number of experiments for which design effort and further definition is required. In addition optimization of both scientific return and utilization of mission resources can be accomplished through increased integration of instruments with synergistic operations and scientific outputs. In order to address these issues a number of activities are ongoing to investigate packages of instruments. As well as detailing the scientific measurements to be made at the surface of the moon, these payload studies provide preliminary concepts for payloads, identify the major challenges for their development and ensure that the mission study properly accounts for the payload and its interfaces.

The Lunar Dust Analysis Package (L-DAP) is an instrument package to determine the microscopic properties of lunar dust including the size distribution of particles from tens nm – 100s μm, the shape and structure of grains, chemical and mineralogical composition of particles. The activity builds on significant experiment heritage obtained through the MECCA experiment package developed for NASA's Phoenix mission (originally defined as a human exploration precursor experiment) [4], the microscope developed for Beagle 2 [5] and MicroOmega on Exomars, the Raman-LIBS elegant breadboard developed in the frame of Exomars [6].

The Lunar Dust Environment and Plasma Package (L-DEPP) is a package to determine the charging, levitation and transport properties of lunar dust, in-situ on the Moon, and the associated properties of the local plasma environment and electric fields. Measurements include charges, velocities and trajectories of levitated dust particles, the temperature and density of the local plasma, electric surface potential, and observations of the radio spectrum (with an additional goal to prepare for future radiation astronomy activities). The L-DEPP study builds on extensive heritage in instrumentation for measurement of space plasmas and the associated environments, dust instrumentation and expertise in radio astronomy [e.g. 7 – 11].

The Lunar Volatile Resource Analysis Package (L-VRAP) is a package to measure the species of volatiles present close to the lunar surface, their abundance and distribution and demonstrate their extraction. The primary mechanism for performing such an analysis is expected to be mass spectroscopy, although additional complimentary measurements may be considered. The potential effects of contamination by the Lander may be critical and so quantifying the likely contamination and its effects are also being investigated. The system applied in the model payload is derived from the Gas Analysis Package on Beagle 2 [12] and the Ptolemy Instrument on Rosetta [13].

Summary: We report on the status of the ESA Lunar Lander mission, emphasizing related science and payload activities.

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The Martian Moon Sample Return mission study MMSR

D. Koschny, D. Agnolon, *ESA/ESTEC, Noordwjik, The Netherlands*, **J. Brucato,** *INAF, Obs. Firenze, Italy***, B. Gondet,** *IAS, Orsay, France***, O. Korablev,** *Space Research Institute (IKI), Moscow, Russia,* **P. Michel,** *Univ. of Nice-Sophia Antipolis, CNRS, Obs. Cote d'Azur, France***, J. Romstedt,** *ESA/ESTEC, Noordwjik, The Netherlands,* **N. Schmitz,** *DLR Berlin, Germany***, K. Willner,** *TU Berlin, Germany***, A. Zacharov,** *Space Research Institute (IKI), Moscow, Russia*

Introduction: ESA is currently studying a mission to return a sample from one of the Martian Moons, either Phobos or Deimos, called Martian Moon Sample Return mission (MMSR). This study is performed as part of ESA's Mars Robotic Exploration Programme. Part of the mission goal is to prepare technology needed for a sample return mission from Mars itself; but the mission should also have a strong scientific justification which is described here.
Science goal: The main science goal of this mission will be to understand the formation of the Martian moons Phobos and Deimos and put constraints on the evolution of the solar system. Currently, there are several possibilities for explaining the formation of the Martian moons:

(a) co-formation with Mars
(b) capture of objects coming close to Mars
(c) Impact of a large body onto Mars and formation from the impact ejecta

The main science goal of this mission will be to find out which of the three scenarios is the most probable one. To do this, samples from one of the Martian moons from the formation time of the moon have to be returned to Earth.
Mission: Spacecraft and payload will be based on experience gained from previous studies to Martian moons and asteroids. In particular the Marco Polo and MarcoPolo-R asteroid sample return mission studies performed at ESA were used as a starting point. In an ESA-internal study in its Concurrent Design Facility, a first mission design for MMSR was developed. The initial starting assumption was to use a Soyus launcher, which the study showed to be marginal if not impossible, in particular for Phobos which is located further into the Martian gravity well. The study showed that unlike the initial Marco Polo study, a transfer stage will be needed. Another main difference to an asteroid mission is the fact that the spacecraft actually orbits Mars, not Phobos or Deimos. It is possible to select a spacecraft orbit which in a Phobos- or Deimos-centred reference system would give an ellipse around the moon. However, because of the locked rotation of the moons, the spacecraft would then always face roughly the same side of the moon.
A further CDF study, based on an Ariane 5 launcher, is planned for spring 2012. Also a short industrial study is planned.
The model payload will consist of a Wide Angle Camera, a Narrow Angle Camera, a Close-Up Camera a visible-IR spectrometer, a thermal IR spectrometer, and a Radio Science investigation. This instrumentation will provide the necessary context measurements needed for a good characterization of the environment of the returned sample.
This paper will present the current status of the mission study from the scientific, technical, and programmatic point of view.

GETEMME: a mission to explore the Martian satellites

C. Le Poncin-Lafitte, *SyRTE - Obs Paris***, V. Lainey,** *IMCCE - Obs Paris***, P. Rosenblatt,** *ROB, Brussels***, J. Oberst,** ***TU Berlin – DLR*****, and the GETEMME core team**

GETEMME (Gravity, Einstein's Theory, and Exploration of the Martian Moons' Environment) is a proposition of mission towards martian's moons. The spacecraft will initially rendezvous with Phobos and Deimos in order to carry out a comprehensive mapping and characterization of the two satellites and to deploy passive laser retro-reflectors on their surfaces. In the second stage of the mission, the spacecraft will be transferred into a lower 1500-km Mars orbit, to carry out routine laser range measurements to the Phobos and Deimos reflectors. Also, asynchronous two-way laser ranging measurements between the spacecraft and stations of the ILRS (International Laser Ranging Service) on Earth are foreseen. An onboard accelerometer will ensure a high accuracy for the spacecraft orbit determination. The inversion of all range and accelerometer data will allow us to determine or improve dramatically on a host of dynamic parameters of the Martian satellites system. From the complex motion and rotation of Phobos and Deimos we will obtain clues on internal structures and the origins of the satellites. Also, crucial data on the time-varying gravity field of Mars related to climate variation and internal structure will be obtained. Ranging measurements will also be essential to improve on several parameters in fundamental physics, such as the Post-Newtonian parameter β as well as time-rate changes of the gravitational constant and the Lense-Thirring effect. Measurements by GETEMME will firmly embed Mars and its satellites into the Solar System reference frame.