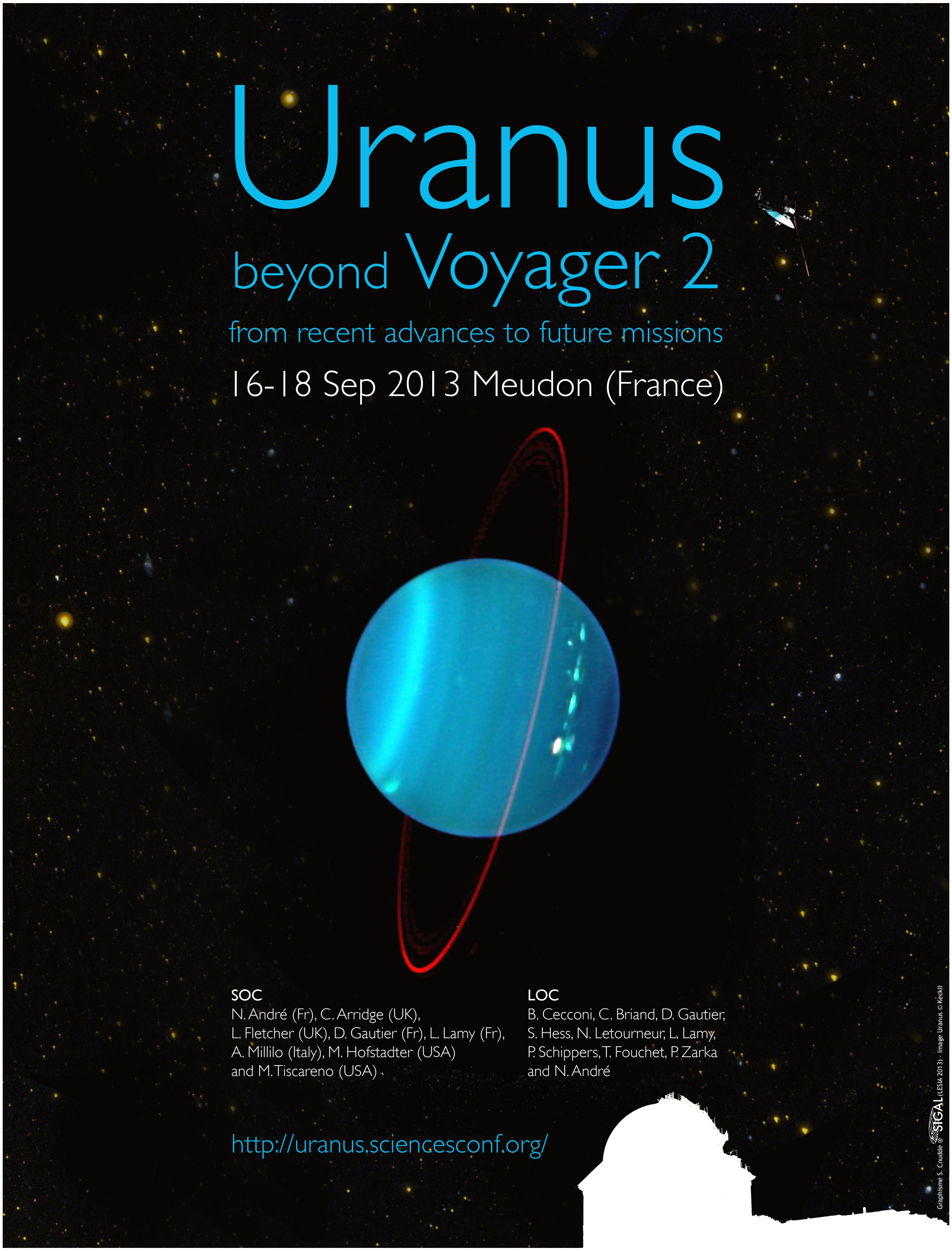

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Book of abstracts

List of sessions :

Session « Interior and origins »

The Formation of Uranus

Ravit Helled (Tel-Aviv University, Israël)

There are many open questions regarding the planet Uranus. The formation mechanism for Uranus is not fully understood, and its composition and internal structure are also not well-constrained. Despite Uranus' similarity to Neptune, the two planets differ in their physical properties such as thermal emission, obliquity, inferred atmospheric enrichment, and possibly, their internal structures. Some of these differences might be related to different formation scenarios, and/or different evolution histories. It is commonly assumed that Uranus had formed by core accretion, the standard mechanism for giant planet formation, in which a planet is formed via core formation followed by gas accretion. However, since Uranus had formed far from the Sun, where the disk's solid surface density is low and the growth timescale is long, it is believed that the disk gas had dissipated before runaway gas accretion occurred. Therefore, Uranus is essentially a failed gas giant. In fact, it seems that Uranus had formed closer to the Sun, and only later arrived to its current location. A hit by a giant impactor appears to be a good explanation for Uranus' tilt and internal structure.In this talk I will discuss Uranus' formation and internal structure, and how the two can be linked together. Implications for understanding extrasolar planets with similar masses will be addressed as well.

Origin of Uranus, collisions among planetary embryos in the middle solar system

Marian Jakubik (Astronomical Institute, Slovak Academy of Sciences, Slovakia)

Modeling the formation of the ice giants Uranus and Neptune is a long-lasting problem in planetary science. Instead of trying to push the runaway/oligarchic growth of planetary embryos up to 10-15 Earth masses, we envision the possibility that the planetesimal disk could generate a system of planetary embryos of only 1-3 Earth masses. Then we investigate whether these embryos could have collided with each other and grown enough to reach the masses of current Uranus and Neptune.

Constraints on the formation conditions of Uranus from in situ composition measurements

Olivier Mousis (Observatoire de Besançon, CNRS, France)

We review the different interpretations that can be made about the formation conditions of Uranus in light of the measurements of its carbon and sulfur abundances. We discuss the formation scenarios that are found consistent with the current knowledge of the composition of the outer solar system.

Is it possible to tilt Uranus without any collision ?

Gwenaël Boué (University of Chicago, USA)
and Jacques Laskar

Uranus' spin axis is tilted by 97 degrees with respect to the normal of its orbits. This particular property is often attributed to an early giant impact between the planet and an Earth-size protoplanet. In this talk, I will present another scenario based on a secular spin-orbit resonance (Boué & Laskar, 2010). I will detail the constraints and the consequences of such a mechanism.

Interior and evolution

Nadine Nettelmann (University of California, USA)

We do not know whether or not Uranus and Neptune have similar structures. While the observational error bars of the pre-Voyager era allowed to explain both planets by the assumption of adiabatic, quasi-homogeneous interiors of similar composition (Hubbard, Icarus, 1978), the tightly constrained Voyager effective temperature and rather low bond albedo values implied low heat fluxes for both planets. Consequently, their picture was turned into that of either super-adiabatic, inhomogeneous interiors, where primordial heat would be trapped in the deep, or into cold, sub-adiabatic interiors (Hubbard et al., in Neptune and Triton, 1995). Upon application of improved EOS data to Neptune, its heat flux was later again found to be consistent with that of an adiabatic, convective interior, while Uranus remained to appear unusually faint (Fortney et al., ApJ, 2011). We note that 'unually faint' refers to a calculated cooling time much longer than the age of the solar system.

In this talk we will see that also Uranus may be adiabatic and convective. Our discussion of Uranus' energy balance and cooling time is partly based on a re-analysis of recent atmosphere models for Uranus and Neptune (Fortney et al., ApJ, 2011), and partly on its received incident flux. We point out that the bond albedo and effective temperature are crucial input parameters in the question about similar interiors. Thus we recommend to reduce their uncertainty through future measurements.

The composition of Uranus & the early evolution of the protosolar disk

Tristan Guillot (Observatoire de la côte d'Azur, CNRS, France)

Uranus probably grasped its outer envelope of hydrogen and helium during the last moments of existence of the circumsolar gas disk. Although subsequent enrichment by planetesimals must be taken into account, the determination of the abundances of key species in Uranus' atmosphere can help us to retrace what happened at the end of the first phase of the formation of the Solar System.

The high-pressure phase diagram of water – implications for the magnetic field of Uranus

Ronald Redmer, Mandy Bethkenhagen (Institute of Physics, University of Rostock, Germany),
Martin French and Sebastien Hamel

The behaviour of warm dense matter (pressures of several Mbar and temperatures of several eV) is of paramount importance for interior and dynamo models of giant planets. However, the high-pressure phase diagram of even the simplest and most abundant elements hydrogen and helium as well as that of molecular systems (e.g. water, ammonia, methane) is not well known. The complexity of the behaviour arises from metal-insulator transitions and demixing phenomena that occur at high pressures. New phases with exotic properties (e.g. super-ionic phases with proton conduction) have been predicted as well. These effects might have a strong impact on the interior and magnetic field of giant planets such as Uranus.

We apply ab initio molecular dynamics simulations based on finite-temperature density functional theory to calculate the equation of state, the high-pressure phase diagram, and the transport properties of warm dense matter for a wide range of densities and temperatures. For Uranus, ab initio results for the EOS and the transport properties of water (French et al., Phys. Rev. 2009, 2010) and ammonia (Bethkenhagen et al., J. Chem. Phys., in press), and methane (S. Hamel, personal communication) are presented and implications for its interior structure are discussed, see e.g. (Redmer et al., Icarus, 2011; Tian and Stanley, Astrophys. J., 2013).

Seismology of Uranus

François-Xavier Schmider (Laboratoire Lagrange, Observatoire de la Côte d'Azur, Université de Nice-Sophia-Antipolis, CNRS, France)

As for the Sun and stars, internal structure of giant planets can be studied by asteroseismology, i.e. by measuring the frequencies of the acoustic eigenmodes of the planet. This possibility was contemplated since 1976, just at the beginning of helioseismology. However, several attempts to detect acoustic modes on Jupiter were unsuccesful until recently. In 2011, Gaulme et al. demonstrated the existence of global oscillations on Jupiter and measured for the first time the jovian fundamental frequency. More recently, observations of density waves in the Saturn's rings by Cassini were attributed to global oscillations of Saturn. Seismology of giant planets enters in a new era, with several projects dedicated to this field, both from ground and from space. Ice giant are even more difficult to observe, because of the limited brightness and small angular size. Ground-based observations would be very difficult. A dedicated instrument onboard of a spacecraft toward the Uranus or Neptune would be required. We will discuss what we expect to learn from seismology about ice giant formation and evolution, and we will present a project dedicated to Uranus exploration.

Session « Magnetic field and magnetosphere»

The uranian magnetic field

Johannes Wicht (MPS, Germany)

The magnetic fields of the ice giants differ from those of any other planet since they are not dominated by a dipole component and have a very complex structure without any obvious symmetry. Based on theoretical grounds and numerical dynamo simulations, at least six different explanations for this peculiar property have been suggested. For example, the density stratification or the radial variations in electrical conductivity are two possible reasons. Other models rely on a stable stratification of deeper layers, a feature often invoked to explain the low luminosity of Uranus. We critically review the different dynamo models, comparing their magnetic spectra to the scarce but nevertheless instructive observations. Of particular interest is also the question whether the models are compatible with refined newer ideas of interior structures and properties.

The magnetosphere of Uranus from Voyager 2

Sébastien Hess (LATMOS, UVSQ, IPSL, CNRS, France)

The magnetosphere of Uranus is certainly the most intriguing planetary magnetosphere in our solar system, mostly because of the large tilts of both the rotational and magnetic axis of Uranus. Information about this magnetosphere is sparse as it was explored only once, during the Voyager 2 flyby of the planet. Since then, the only observations in relation with the magnetosphere of Uranus are a few observations of auroras. I will present a review of the observations and measurements performed by Voyager 2 in the magnetosphere of Uranus, and present the picture of the magnetosphere dynamics that has been drawn for them.

Uranus radiation environments: lessons learnt from giant planet magnetosphere

Angélica Sicard-Piet (ONERA-The French Aerospace Lab, France)

Since the 1990s, ONERA has developed a physical model of the Earth radiation belts, called Salammbo 3D. During the early 2000s, this model has been adapted to Jupiter environment, and then to the case of Saturn few years ago. Salammbô models include the main physical processes that govern the particles of the radiation belts. These models have been successfully compared to measurements and, for the Jovian case, to radioastronomy images. From lessons learned from these modelling activities we plan here to review the main characteristics of radiation belts in the vicinity of magnetised body illustrated with Earth, Jupiter and Saturn environment and to investigate any similarities between those environments and Uranus radiation environment. We will show how the same fundamental physical processes (radial diffusion, interactions with rings/moons …) could be applicable to Uranus taking into account the specificity of its environment : particularly the large tilt of the magnetic field.

The search for H_3^+ auroral signatures from Uranus

Henrik Melin (University of Leicester, UK)

The molecular ion H_3^+ is formed via the ionisation of molecular hydrogen. In the upper atmosphere of Uranus, the ionisation energy is provided by both solar radiation and particle precipitation of magnetospheric origin. Whilst the solar contribution is expected to create a uniformly glowing ionosphere, the particle precipitation is centred on the magnetic poles, which rotate in and out of view, creating a modulation in H_3^+ brightness as the planet spins on its axis. Here, we present infrared ground-based observations of Uranus using Keck, VLT, Gemini and the NASA IRTF to characterise the short-term variability of the H_3^+ emission.

Uranus aurorae from solstice to equinox

Laurent Lamy (LESIA, Observatoire de Paris, CNRS, France)

The recent re-detection of Uranus aurorae with the Hubble Space Telescope, 25 years after their discovery by Voyager 2, provided new insights for investigating the asymmetric magnetosphere of Uranus. Here, I will review the set of auroral signatures identified in images and spectra obtained by HST in the Far-UV domain, which probes neutral species of the upper atmosphere. I will then analyze their characteristics and discuss the implications for the uranian magnetosphere and its highly variable interaction with the solar wind flow from near-solstice (1986) to near-equinox (2011) configurations.

Response of Uranus' auroras to solar wind compressions at equinox

Stanley W. H. Cowley (University of Leicester, UK)

We consider open flux production and magnetic tail formation for the unique physical circumstances at Uranus, where the planet's spin axis lies close to the orbit plane, while the magnetic dipole has a large ~60° inclination to the spin axis. Under these circumstances open flux production and transport into the nightside can in principle occur continuously for near-solstice conditions, leading to the formation of a well-developed bi-polar rotating magnetic tail, as observed during the Voyager 2 fly-by in 1986. However, it is argued that tail formation will be significantly inhibited near to equinox, as open tubes are wound over the dayside magnetopause by planetary rotation, thus reducing further open flux production, and are compressed together north or south of the planet promoting 'tail' reconnection and open flux closure. If so, this may account for the weak auroral responses to predicted solar wind compressions of Uranus' magnetosphere reported recently from Hubble Space Telescope observations under near-equinoctial conditions. Major auroral responses are observed following strong compressions at Earth and Saturn resulting from rapid and substantial closure of pre-existing open flux in the tail. The lack of such a response at Uranus near equinox may thus reflect the lack of a well-developed tail under these conditions.

Uranus dayglow and auroral signatures

Mathieu Barthélémy (IPAG, Université Joseph Fourier, CNRS, France),
Laurent Lamy and Gaël Cessateur

Recent observations of Uranus allow us to re-detect an auroral emission of Uranus during the progression of an interplanetary shock (Lamy et al., GRL, 2012). The ice giant atmospheres are mainly composed of hydrogen in atomic and molecular form. Thus dayglow and auroral emission are mainly composed of H2 Lyman and Werner bands, H-lyman emission in the UV and H_3^+ emissions in the infrared. We will review the recent advances concerning these emissions especially the different diagnostic they allow about the upper atmosphere of Uranus and its interaction with the magnetosphere. We will also asses the needs in term of model and observation for future more accurate characterizations of the upper atmospheric emissions of these planet.

Session « The science case for a cruise phase in the outer heliosphere »

Solar wind processes in the outer heliosphere

Carine Briand (LESIA, Observatoire de Paris, CNRS, France)

The long cruise period to Uranus is a unique opportunity to study numerous processes in the solar wind, under physical conditions rarely encountered. Since Voyager, no mission has explored the far outer space for plasma physics studies. After the launches of Solar orbiter and Solar Probe Plus which both will explore the inner heliosphere, a mission to Uranus would allow to put new constraints on several physical plasma processes. During this talk, we will present the benefits we could expect from such a mission for the studies on magnetic holes, interplanetary shock waves, turbulence, plasma waves etc.

Test of General Relativity during Interplanetary Cruise to the Uranus System

Bruno Christophe (ONERA-The French Aerospace Lab, France)

General Relativity, the current theoretical formulation of gravitation, is in good agreement with most experimental tests of gravitation. But General Relativity is a classical theory and all attempts to merge it with the quantum description of the other fundamental interactions suggest that it cannot be the final theory of gravitation. Meanwhile, the experimental tests leave open windows for deviations from General Relativity at short or long distances.

General Relativity is also challenged by observations at galactic and cosmic scales. The rotation curves of galaxies and the relation between redshifts and luminosities of supernovae deviate from the predictions of the theory. These anomalies are interpreted as revealing the presence of new components of the Universe, the so-called "dark matter" and "dark energy" which are thought to constitute respectively 25.8 % and 69.4 % of the energy content of the Universe according to most recent estimations after the results of PLANCK. Their nature remains unknown and, despite their prevalence in the energy content, they have not been detected up to now by other means than gravitational measurements.

Given the immense challenge posed by these large scale observations, in a context dominated by the quest for the nature of dark matter and dark energy, it is important to explore every possible explanation including the hypothesis that General Relativity is not the correct description of gravity at large scales.

This paper will describe a test of General Relativity proposed during the interplanetary cruise towards outer planet. For this test, a precise navigation of the probe is necessary in order to monitor the trajectory and compare it to the prediction of General Relativity. For that purpose, it is mandatory to add to the radio-science measurement, which gives the motion of the spacecraft, an accurate accelerometer in order to deduce which part of this motion is due to the non-gravitational forces exerted on the spacecraft (solar radiation pressure, thermal force from the RTG), allowing to avoid any misinterpretation of any anomaly in the navigation.

Small Bodies en route to the far Solar System

Geraint Jones (UCL Mullard Space Science Laboratory and the Centre for Planetary Sciences at UCL/Birkbeck, UK)

A mission to Uranus would present an excellent opportunity to carry out observations of small bodies during the spacecraft's long journey to its ultimate target. Such targets may be attainable without a major sacrifice of delta-V. The scientific value of such small body observations has been demonstrated amply by the encounters of Galileo with Ida and Gaspra, Rosetta with Lutetia, and several others. We shall present an overview of the possible science that can be carried out during such encounters. In addition to the more obvious remote sensing measurements, particles and fields instruments can sense the nature of the interaction between these bodies of the solar wind, searching for weak magnetic fields and possible gaseous emission from the encountered bodies. We shall also present the benefits to the instrument and operations teams of such encounters to test and calibrate their instruments comprehensively before arrival at the Uranus system.

Large-scale structures in the solar wind between the Sun and 20 AU

Alexis Rouillard (IRAP, Université Paul Sabatier, CNRS, France)

We will review magnetic field and plasma measurements of large-scale solar wind structures observed between the Sun and Uranus. Solar wind flows inside 1AU are complex, typically showing numerous small streams, transient flows and shocks as well the recurrent signatures of corotating streams. From 1 to 10 AU the largest corotating streams sweep up the slower flows (transient and/or corotating streams) and shocks. This produces single large-amplitude compression waves. As a result of this sweeping process, memory of the sources and flow configurations near the sun is lost. This means that in the outer solar system the structure of the solar wind is dominated by large scale pressure waves separated by several AU. Between 10 and 20AU, these merged interaction regions tend to be bounded by forward and a reverse shocks with additional weaker shocks. This processing of large-scale solar wind structures has a strong effect on the propagation of galactic cosmic rays diffusing through the solar wind magnetic field fluctuations. The magnetic field fluctuations and shocks convected outward by these merged interaction regions scatter galactic cosmic rays and are associated with long-lasting Forbush decreases near Earth.

Session « Atmosphere and ionosphere »

Uranus' Deep Atmospheric Structure and Composition

Mark Hofstadter (Jet Propulsion Laboratory, California Institute of Technology, USA)

The focus of this review talk is the troposphere of Uranus, at pressures between about 1 and 100 bars. Most of what we know about this region comes from ground-based observations at visible, infrared, and radio wavelengths, with important constraints imposed by gravity data, chemical and dynamical modeling of the atmosphere, and of course Voyager temperature and composition information near the upper boundary of the region to be discussed. Knowledge of the deep atmosphere is crucial for advancing some of the priority science objectives which various reviews have identified for the Ice Giants. Principal among these are the atmospheric composition, isotopic ratios of key species, winds and other dynamical features, and energy transport through this region.

Visible and IR imaging have shown the stratosphere and upper troposphere (down to perhaps a couple bars) to have clear seasonal, meridional, and zonal variability in cloud structure, hydrocarbon abundances, and temperature (e.g. Orton et al. 2013, in preparation; Sromovsky et al., Icarus, 2012; Irwin et al., ApJ, 2007). Deeper down, radio data show order-of-magnitude mixing ratio variations in condensible species (NH_3, H_2S, perhaps H_2O) between the poles and equator, with even stronger gradients with altitude (e.g. Hofstadter et al., Icarus, 2003; de Pater et al., Icarus, 1989). The data are somewhat ambiguous regarding seasonal change in these patterns at depth (e.g. Kramer et al., A&A, 2008 ; Klein and Hofstadter, Icarus, 2006).

While it is generally accepted that convection, circulation patterns, and condensation are the prime drivers of the temporal and spatial variability seen, dynamical models have not been able to recreate all the observed features (e.g. Friedson et al., BAAS, 2012; Le Beau et al., BAAS, 2012). Similarly, aqueous chemistry has long been invoked as the likely mechanism for explaining the strong sub-solar NH_3/H_2 and NH_3/H_2S ratios inferred for the mid-troposphere, but current chemical models do not create the magnitude of the observed depletion in NH_3 (Atreya et al., BAAS, 2006).

Observations with new ground-based telescopes, coupled with advances in dynamical and chemical modeling, promises to resolve many of the open questions about Uranus and Ice Giants in general. It is clear, however, that some fundamental questions about their formation and evolution can only be answered with a dedicated mission to an Ice Giant system.

A comparative study of Uranus and Neptune with Herschel

Emmanuel Lellouch (LESIA, Observatoire de Paris, CNRS, France),
R. Moreno, T. Cavalié, H. Feuchtgruber, G. Orton, C. Jarchow, P. Hartogh, B. Swinyard
and the HssO team

With similar masses and radii, the "icy giants" Uranus and Neptune appear as twins in the Outer Solar system. Yet, past observations have revealed important differences. In particular, Uranus is the only Giant Planet without a measurable energy source. As compared to Neptune, this results in a less active meteorology, a weaker convection, and a less-rich atmospheric composition with a lower homopause.

Uranus and Neptune have been observed on multiple occasions by Herschel SPIRE, PACS and HIFI, both for calibration purposes and within the HssO GTKP (Hartogh et al, Planet. Space Sci., 2009) as well as two OT programs. The observations consist of full range spectra with PACS and SPIRE, and dedicated line observations with PACS (H_2O, CH_4, HD) and HIFI (H_2O, CO, CH_4). Highlights of the observations are (i) the first detection of the pure rotational lines of methane in these atmospheres (ii) the first spectrally resolved observations of H_2O in the two objects (iii) the first detection of CO in Uranus in thermal radiation and the complete observation of the CO spectrum in Neptune from 150 micron to the mm range (iv) the first detection of the HD R(0) and R(1) lines in both objects.

Modelling of the observations confirms that Neptune's stratosphere is ~10 times richer in methane than Uranus (Lellouch et al., A&A, 2010 ; Moreno et al., DPS, 2012). CO is also ~ 2 orders of magnitude less abundant in Uranus (Cavalié et al., in prep., Cavalié et al. ; this conference) than in Neptune, where the CO distribution increases with altitude (Lellouch et al., A&A, 2010 ; Moreno et al., in prep.). These differences are probably related to differences in the convective states of the objects and their temperature fields. In contrast, the two planets exhibit indistinguishable D/H ratios, which are only moderately enhanced with respect to the protosolar values (factor ~2) (Feuchtgruber et al., A&A, 2013). Using interior models from the literature and assuming that complete mixing of the atmosphere and interior occured during the planets history leads to a (D/H) ratio in the protoplanetary ices that formed these planets that is significantly less than the values in comets. Possible ways out of this problem is that Uranus' and Neptune' are actually more rock- than ice-rich, or that the planets have never been fully mixed.

First submillimeter observation of CO in the stratosphere of Uranus with Herschel-HIFI

Thibault Cavalié (Laboratoire d'Astrophysique de Bordeaux, CNRS, France)

Oxygen-rich deep interiors of the Giant Planets (Hersant, et al., Planet. Space Sci., 2004) cannot explain the discovery of water vapor and carbon dioxide in the stratospheres of the Giant Planets by (Feuchtgruber et al., Nature, 1997) because these species are trapped by condensation around their tropopause levels (except CO_2 in Jupiter and Saturn). Therefore, several sources in the direct or far environment of the Giant Planets have been proposed: icy rings and/or satellites (Strobel and Yung, Icarus, 1979), interplanetary dust particles (Prather et al., ApJ, 1978) and large comet impacts (Lellouch et al., Nature, 1995).

Infrared Space Observatory (ISO), Cassini, Odin and Herschel observations have proven that the Jovian stratospheric water and carbon dioxide originate from the Shoemaker-Levy 9 comet impacts in July 1994 (Lellouch et al., Icarus, 2002 ; Cavalié et al., A&A, 2013), while Herschel has recently shown the external flux of water at Saturn and Titan is most likely due to the Enceladus geysers and the water torus they feed (Hartogh et al., A&A, 2011 ; Moreno et al., Icarus, 2012).

As for carbon monoxide (CO), the emerging picture seems to show more uniformity for its sources. Because CO does not condense at the tropopauses of Giant Planets, oxygen-rich interiors are a valid source. An internal component has indeed been observed in the vertical profile of CO in Jupiter by (Bézard et al., Icarus, 2002) and in Neptune by (Guilloteau et al., A&A, 1993), while an upper limit has been set on its magnitude by (Cavalié et al., Icarus, 2009) for Saturn. In addition to interiors, large comets seem to be the dominant external source of CO in the Giant Planets, as shown by various studies: (Bézard et al., Icarus, 2002) and (Moreno et al., Planet. Space Sci., 2003) for Jupiter, (Cavalié et al., A&A, 2010) for Saturn and (Lellouch et al., A&A, 2005) for Neptune. Despite its first detection almost a decade ago by (Encrenaz et al., A&A, 2004), the situation has remained unclear for Uranus ever since. The (sub)millimeter domain with the use of heterodyne spectroscopy has long been considered as promising to determine the vertical profile of CO, and thus its origin, in Uranus (e.g. Rosenqvist et al., ApJ, 1994). However, attempts made to detect the molecule have failed so far in this spectral range, leading only to upper limits (Cavalié et al., A&A, 2008). In this paper, we present the first submillimeter detection of CO in Uranus carried out with the HIFI instrument (de Graauw et al., A&A, 2010) onboard the Herschel Space Observatory (Pilbratt et al., A&A, 2010) in 2011-2012. Using a simple transport model, we review the various possible sources of CO (internal and external) and constrain their magnitude. For instance, we derive an upper limit for the internal source of CO. And with the thermochemical model of (Venot et al., A&A, 2012), adapted to the interior of Uranus, we derive an upper limit on its deep O/H ratio from it.

Constraints on the atmosphere of Uranus from the infrared: Earth-based and potential spacecraft observations

Glenn Orton (Jet Propulsion Laboratory, California Institute of Technology, USA)

Models for the mean thermal structure and composition of the atmosphere of Uranus can be derived from a suite of spacecraft and ground-based observations. In theory, the shape of the hydrogen collision-induced absorption in the mid-infrared can determine the He/H2 ratio, with additional constraints on the vertical distribution of CH_4 in the stratosphere with models for the vertical mixing that are consistent with the mixing ratios of hydrocarbons whose abundances are primarily influenced by dynamics rather than chemistry. Spitzer and Hershel data provide substantial constraints on the abundances and distributions of CH_3, CH_4, C_2H_2, C_2H_6, C_3H_4, C_4H_2, H_2O and CO_2. At millimeter wavelengths, strategic ground-based observations from the United Kingdom Infrared Telescope (UKIRT) and Caltech Submillimeter Observatory (CSO) atop Mauna Kea, Hawaii, provide evidence that an additional opacity source in Uranus is required besides (i) the H_2 collision-induced and absorption, including significant dimer contributions, and (ii) the NH_3 absorption that is consistent with the longer-wavelength microwave spectrum. The most likely candidates for such absorption are H_2S and $PH_{3.}$ Further Earth-based observations have determined broad regions of temperature variability in the atmospheres, and Spitzer has determined the existence of variability across the planet by investigating its light curve. Further insight into the atmosphere can be gained by strategic measurements of mid- to far-infrared thermal emission that cover spatial resolutions that are unavailable from the Earth. These are as critical to understanding the neutral atmosphere as are measurements of cloud-tracked wind motions; thus, if investigation of the atmosphere is a science goal of a mission, at least one of the instruments on board should operate in the mid- to far-infrared range.

The Clouds of Uranus

Patrick Irwin (University of Oxford, Atmospheric, Oceanic and Planetary Physics, UK)

The Voyager 2 flyby of Uranus in 1986 revealed a world that appeared extraordinarily quiescent, with an almost entirely uniform appearance at all latitudes and longitudes and very few cloud features. In addition, the measured temperature structure suggested almost complete thermal balance with respect to the incident sunlight and thus an absence of an internal reservoir of heat, quite unlike any of the other giant planets. Since this encounter, which was close to Uranus' summer solstice, continually improving ground-based observations have revealed a remarkable change in Uranus' appearance, with a dramatic increase in cloud activity, and the formation of a bright cloud zone at 45S, which dimmed through the planet's northern summer equinox in 2007 as a new zone formed at 45N. In this paper we will review the seasonal changes in Uranus' cloud features and present recent attempts to interpret these features through modelling of their visible and near-IR reflectance spectra and the resulting inferences made on Uranus' vertical cloud structure at different locations and the abundance of methane.

Clouds and Storms in Uranus' Upper Troposphere

Imke de Pater (UC Berkeley, AURA, Univ. Wisconsin-Madison, USA),
Heidi Hammel, Larry Sromovsky and Patrick Fry

We have been monitoring Uranus at near-IR wavelengths with the 10-m Keck telescope and its adaptive optics system since the turn of the century. In this presentation we will give an overview of the data, with special emphasis on the polar regions (polar cap, collar and cloud features) and large storm systems (e.g., the Berg).

Overview of the Zonal Wind Structure of Uranus

Heidi Hammel (Association of Universities for Research in Astronomy, USA),
Larry Sromovsky, Patrick Fry and Imke de Pater

Our early knowledge of the zonal wind structure of Uranus was informed solely by measurements from the Voyager 2 spacecraft flyby in 1986. Since then, the combined power of the Hubble Space Telescope and adaptive optics imaging from the Keck Observatory have hugely increased our understanding of uranian winds. The 2007 equinoctial observational program yielded a comprehensive view of the global zonal structure. Post equinox-observations from 2009 to 2011 firmly established the presence of a high latitude northern jet near 60 N. The most recent Keck observations, using a refined processing technique, have revealed an unprecedented level of atmospheric detail on Uranus. In this presentation, I will review our knowledge of the overall zonal wind structure of Uranus.

Simulating the Meteorology of Uranus with General Circulation Models

Raymond LeBeau (Saint Louis University, USA)

The approach to general circulation modeling for Uranus is in many ways similar to that of the other giant planets. However, Uranus also presents challenges common only to the other Ice Giant, Neptune and some challenges unique to itself. These challenges emerge from the observed meteorology of the planet. In contrast to the other giant planets. the zonal winds on Uranus and Neptune are defined by only a few broad jets, leading to atmospheric dynamics that are more global. Also unlike Jupiter and Saturn, observed vortices on Uranus and Neptune are distinct and infrequent occurrences. And of course the dramatic seasonal changes from the Voyager II Uranus of solstice to the past decade of observation about equinox present a unique challenge for any long-term simulations of this atmosphere.

These observations and others drive the efforts on Global Circulation Models, efforts that range from capturing thermally-driven circulations to determining the driving physics of the zonal wind. Our focus is on simulating clouds and spots, the visible meteorology of the Uranian atmosphere. This requires the combining of cloud microphysics and atmospheric dynamics, placing new demands on the numerics underlying the simulations. However, these developing simulations have already suggested unexpected complexities. For example, the evolution of the Uranian Dark Spot may have been strongly dependent on the development of companion clouds and the local distribution of condensable species. With further development, this model will be able to represent the visible features of the atmosphere of Uranus, thereby creating a more powerful tool for understanding past and future observations.

Upper atmosphere and ionosphere

Tom Stallard (University of Leicester, UK)

Our understanding of the upper atmosphere and ionosphere of Uranus comes from a combination of Voyager measurements, as well as a continuing programme of ground-based observations over the past three decades, a long-term study that has revealed thermal changes over an extended period, which are currently not understood. This presentation will discuss the configuration of the upper atmosphere observed by Voyager and how that has appeared to change in the intervening time.

Session « Moons »

The surface and interior of the Uranian moons

Gabriel Tobie (LPG Nantes, University of Nantes, CNRS, France)

The five largest moons of Uranus (Miranda, Ariel, Umbriel, Titanian,Oberon) are comparable in sizes and orbital configurations to the medium-sized moons of Saturn. They are, however, characterized by larger mean densities, about 1.5 g/cm3 in average, and by different insulation patterns, with their poles directed towards the sun, owing to the large axial tilt of the planet. The observations performed during the flyby of Voyager 2 revealed signs of endogenic resurfacing associated with tectonic stress, possibly involving cryovolcanic processes, especially on the moons Ariel and Miranda with the youngest surfaces. However, only very limited observations were possible during Voyager 2's brief encounter, at which time only the southern hemispheres of the satellites were illuminated. The diversity of the medium-sized icy satellites at Uranus and, indeed, throughout the solar system, demonstrates the complex and varied histories of this class of object. Their exploration provides a unique opportunity to understand how mid-sized moons can remain geologically active over prolonged periods of time.

As in the Jovian and Saturnian system, tidal interaction is likely to have played a key role in the evolution of the Uranian satellite system. Intense tidal heating during sporadic passages through resonances is expected to have induced internal melting in some of the icy moons. Such tidally induced melting event may have triggered the geological activity that led to the late resurfacing of Ariel. The two largest moons, Titania and Oberon, with diameters exceeding 1500 km, might still harbor liquid water oceans between their outer ice shells and inner rocky cores, remnants of past melting events. Moreover, as most of the surface of these worlds have not been imaged by Voyager 2, a complete mapping of the surface by the Uranus Pathfinder may reveal unexpected signs of recent endogenic activity. Just as the Cassini's study of Enceladus has transformed our understanding of the dynamic evolution of medium-sized icy moons, Uranus Pathfinder will reveal the nearly unexplored Uranian satellites and facilitate comparative study of icy satellites in the solar system.

Are the faults in the Arden and Inverness Coronae region on Uranus' satellite Miranda listric in geometry?

Chloe Beddingfield (University of Tennessee, USA),
Devon M. Burr and Joshua P. Emery

Miranda is a ~470 km diameter Uranian icy satellite with a surface that exhibits complex tectonic structures localized in three regions termed coronae. Ridges and troughs at the outer region of Arden Corona have been interpreted as normal fault blocks. We investigate the hypothesis that these faults are listric in geometry. Our alternative hypothesis is that the faults are planar. On Earth, listric faults are concave upwards, curved faults that decrease in dip with increasing depth and sole into a sub-horizontal detachment surface. The detachment surface separates material with different rheologies, and may be located at the brittle-ductile transition zone.

To test the hypothesis of a listric geometry, we analyze the fault geomorphology. The fault blocks in a listric system are expected to be tilted with scarp dips that progressively decrease in the down-dip direction, reflecting the subsurface transition into the detachment surface. In this context, down-dip is radial from the coronae. The blocks would also exhibit back-tilted faces that would increase in slope radially outward from the coronae. Listric scarps with enough displacement may display evidence of concavity. Rollover structures are common on the boundaries of listric fault systems, slope in the opposite direction of the faults, and may include antithetic normal faults.

Limb view images were used to measure the dips of fault scarps and slopes of back-tilted faces on fault blocks within the Arden Corona boundary, and to inspect for evidence of a rollover structure. Overlapping plan view images were used to create a digital elevation model (DEM) for measuring dips on two fault blocks between Arden and Inverness coronae.

Our results show that the fault blocks in the Arden and Inverness region are tilted, and their angles of dip decrease in the down-dip direction. Their back-tilted face slopes tend to increase in this direction within the Arden Corona boundary, although not in the region between Arden and Inverness. A feature within the outer margin of Arden slopes in the opposite direction of the fault system and may exhibit an antithetic normal fault which is consistent with a rollover structure. Results of fault scarp concavity measurements are not statistically significant, possibly due to DEM resolution limitations.

In aggregate, these results better support the primary hypothesis that the faults in the Arden and Inverness Coronae region are listric over the alternative hypothesis that they are planar. If analogy with terrestrial structures is valid, the listric character of the faults suggests that a subsurface detachment layer is present, and may have occurred at Miranda's brittle-ductile transition zone at depth at the time of faulting. Based on this result, measurements of the fault geometry can be used to constrain the depth to the detachment surface and to estimate the depth to a possible brittle-ductile transition zone. Estimates of this depth will be provided.

Spectral properties of Uranian moons: are they coated with dust from irregular satellites?

Josh P. Emery (University of Tennessee, USA),
R. Cartwright, A.S. Rivkin and D.E Trilling

Near-infrared spectra of the regular satellites of Uranus reveal abundant surface H_2O ice. Low albedos and reddish visible colors, as compared to similar-sized moons of Saturn, indicate the presence of a dark, refractory material along with the H_2O ice. The composition, relative abundance, and source of this dark material, as well as H_2O grain size, remain poorly constrained. Analysis of spectral color maps made using Voyager 2 Imaging Science System (ISS) data shows that the leading hemispheres of Ariel, Umbriel, Titania, and Oberon are spectrally redder than their trailing hemispheres (2%, 5%, 8%, 22% leading/trailing color difference, respectively) (Buratti and Mosher, 1991). The observed trends in spectral reddening (greater reddening on the *leading* hemispheres of the satellites *furthest* from Uranus) is consistent with the accumulation of exogenic dust that originated from collisional grinding of irregular satellites (Bottke et al., 2010). Furthermore, the reduced H_2O ice band depths observed on the leading hemisphere of Oberon (Grundy et al., 2006) are consistent with accumulation of exogenic material, which could be obscuring the signature of H_2O ice on its surface.

We are therefore investigating H_2O band depths and spectral color, as a function of satellite longitude, in order to test the hypothesis that the leading hemispheres of Ariel, Umbriel, Titania, and Oberon are coated by dust that originated on the surfaces of retrograde irregular satellites. To do this, we are analyzing spectroscopic data gathered by our team, as well as data gathered by (Grundy et al., 2006), using the SpeX spectrograph at the Infrared Telescope Facility (0.8 – 2.4 μm, R ~750 – 1200), and visible wavelength photometric data gathered using the MORIS Camera, co-mounted with SpeX. We will compare our MORIS data to Voyager 2 ISS data in order to determine whether the spectral reddening detected by (Buratti and Mosher, 1991) over the southern hemispheres of the large Uranian satellites extends to their northern hemispheres. In this presentation, we will summarize the present state of knowledge regarding the distribution and spectral properties of dark material and H_2O ice on these moons, and we will present initial results from our ongoing telescopic observations.

Distribution of CO2 ice on the four largest Uranian Satellites

Richard Cartwright (University of Tennessee, USA),
J.P. Emery, A.S. Rivkin and D.E. Trilling

Ground-based observations of the regular Uranian satellites have detected crystalline H_2O ice mixed with a spectrally flat constituent, probably carbonaceous in origin (e.g. Soifer et al., 1981; Brown and Cruikshank, 1983; Brown and Clark, 1984). Near-infrared observations of these satellites have revealed CO_2 ice combination and overtone bands (between 1.5 – 2.2 μm) on Ariel, Umbriel, and Titania (Grundy et al., 2003; 2006). These CO2 ice bands are strongest on the trailing hemispheres of these satellites and decrease with increasing orbital radius, with non-detection on the most distant regular satellite Oberon (Grundy et al., 2006). The observed trends in CO_2 ice (greater abundance on the trailing hemispheres of the satellites closest to Uranus), is consistent with the production of CO_2 ice via charge particle bombardment of H_2O ice and carbon-rich surface materials.

Thus, we are investigating the distribution and abundance of CO_2 ice on the surfaces of Ariel, Umbriel, Titania, and Oberon, as a function of satellite longitude, in order to test the hypothesis that magnetospherically-driven radiolysis is altering the surface composition of these satellites. To do this, we are analyzing spectroscopic data gathered by our team, as well as data gathered by (Grundy et al., 2006), using the SpeX spectrograph at the Infrared Telescope Facility (0.8 – 2.4 μm, R ~750 – 1200), and photometric data gathered by the Infrared Array Camera onboard the Spitzer Space Telescope (four channels, centered near 3.6, 4.5, 5.8, and 8.0 μm). By combining these datasets, we will characterize the abundance of CO_2 ice as a function of satellite longitude, looking for trends in this volatile's distribution. We will summarize the current state of knowledge regarding the distribution of CO_2 ice on the four largest Uranian satellites, and we will present our results from ongoing telescopic observations.

Session « Rings and dynamics »

Recent Advances in our Understanding of the Rings and Inner Moons of Uranus

Mark Showalter (SETI Institute, USA)

We have been observing the rings and small moons of Uranus with the Hubble Space Telescope during most of the years between 2003 and 2013. These observations included the period around Uranus's December 2012 equinox, when the ring system was almost exactly edge-on as seen from Earth. This observing program has led to the discovery two small moons (Mab and Cupid), the recovery of a third moon (Perdita), and the discovery of two faint rings (mu and nu). This work has also demonstrated that the perturbations by Ophelia and Cordelia induce width variations in the epsilon ring, which are detectable from Earth as subtle variations in the ring's brightness.

The results raise many interesting questions about the formation and evolution of the Uranus system. For example, the mu ring shares an orbit with Mab, and is probably composed of dust that has been raised off of its surface. However, no other moon seems to raise a cloud of dust, and the nu ring is not associated with any known moon. Furthermore, the mu ring is distinctly blue in color, which indicates that is has a very unusual distribution of particle sizes.

Astrometry reveals that all of the moons show subtle variations in their orbits, from which one will likely be able to infer their dynamical masses. The nine moons orbiting between semimajor axes of 59,170 and 76,400 km are the most densely-packed set of moons in the solar system, and numerical integrations predict chaotic interactions leading to collisions on time scales of less than one million years. Cupid, in particular, is on a precarious orbit just ~ 600 km interior to the orbit of the much larger Belinda. Mab, although well isolated from the others, also shows orbital variations on a time scale of years that are not understood.

On the long-term dynamical evolution of the main satellites of Uranus

Emilie Verheylewegen (Namur Center for Complex Systems, Naxys, University of Namur, Belgium),
Benoit Noyelles, Ozgur Karatekin and Anne Lemaitre

Voyager II mission that explored the Uranian system and its main satellites in 1986, revealed a combination of geophysical and dynamical abnormalities. These abnormalities can be explained as a set by a complete orbital-thermal model : in particular the resurfacing of Miranda combined with its high orbital inclination (≈ 4.338◦) currently observed could be explained by a capture in the past in a 3:1 mean motion resonance with Umbriel. The dynamical part of the problem has already been studied by several authors 20 years ago (Dermott et al., 1988; Tittemore & Wisdom, 1989; Malhotra 1990; Moons & Henrard, 1993) and revisited by us with other powerful numerical tools (Verheylewegen et al., submitted). We have in particular analyzed the different secondary resonances that the system might have encountered. In parallel, we are working on a thermal model using the evolution of the temperature inside the satellite, with radiogenic and tidal heating sources. The analytical expressions of the viscosity and the rigidity allow to compute new tidal parameters at each step of the evolution to inject them in the orbital part of the model. The objective is to show the first results of the combination of the two parts during the evolution through the mean-motion resonance 3:1 between Miranda and Umbriel.

Impact generated rings in the Portia family region

Rafael Sfair (UNESP - Campus de Guaratinguetá, Brazil)

The Portia group is a set of nine small satellites densely packed within 2 and 3 radii of Uranus, and some of these moons are related to faint rings : the nu ring orbits between Portia and Rosalind, while the mu ring peak is aligned with the orbit of Mab. (Sfair & Giuliatti Winter, 2012) showed that the alignment and the triangular radial profile of the mu ring may be explained by a combination of the dust ejection caused by the bombardment of micrometeoroids onto the surface of Mab, and the subsequent effects of the planetary oblateness and the solar radiation force acting upon the grains. In spite of all members of the Portia family are subject to a similar flux of impactors and forces, so far there is no evidence of other ring paired with a satellite. We found that a possible exception is Bianca, the innermost member of the family, and therefore less sensitive to observations. With an appropriate size for a ring-producing moon, our calculations suggests that the bombardment may provide material to the surroundings at a rate of 40 g/s. The solar radiation force effects can be noticed in an asymmetrical triangular distribution of the ejected grains, and in the slight offset between the density peak of the resulting ring and Bianca's orbit. In our numerical simulations the dust grains can survive in the region up to 8000 years, when all dust particles are removed by collisions with the source body. This survival time allows us to estimate an upper limit of 1E-4 for the optical depth of this hypothetical ring, but a more accurate model is necessary to place better constrains for future observations.

Orbital Chaos as the Generator of the Leading/Trailing Color Asymmetries of the Uranian Regular Satellites

Daniel Tamayo (Cornell University, USA),
J.A. Burns and D.P. Hamilton

The anomalously flat size distribution of the irregular satellites suggests a violent collisional history that would have generated vast quantities of dust at the outer reaches of Uranus' Hill sphere early in the Solar System's history (Bottke et al., 2010). These dust grains would have then migrated in toward the planet as radiation forces caused their orbits to decay (Burns et al., 1979). Because of Uranus' extreme obliquity, Tremaine et al. (2009) find that the orbits of large objects are unstable to eccentricity perturbations in the radial range $a \approx 60 - 75\ R_p$. We study the dynamics of infalling dust at this extreme obliquity by considering the added effect of radiation pressure, which strongly affects small grains.

We find that the unstable zone persists, though radiation pressure shifts its radial location (Tamayo et al., 2013a). Upon entering this region, we find that dust orbits undergo chaotic large-amplitude eccentricity oscillations that bring their pericenters inside the orbits of the regular satellites. We argue that the impact probabilities and expected spatial distribution across the satellite surfaces provide the best explanation for the observed leading/trailing color asymmetries (Buratti & Mosher, 1991) common to the outer four main satellites (Tamayo et al., 2013b).

Uranus main ring system

Imke de Pater (UC Berkeley, TU Delft, SETI, AURA),
David Dunn, Daphne Stam, Mark Showalter, Heidi Hammel et al.

We present observations of the uranian ring system at a wavelength of 2.2 micron, taken between 2003 and 2008 with NIRC2 on the W.M. Keck telescope in Hawaii, and on 15-17 August 2007 with NaCo on the Very Large Telescope (VLT) in Chile. Of particular interest are the data taken around the time of the uranian ring plane crossing with Earth on 16 August 2007, and with the Sun (equinox) on 7 December 2007. We model the data at the different viewing aspects with a Monte Carlo model to determine: 1) the normal optical depth, location and radial extent of the main rings, and additionally the vertical extent of the dusty rings. We find that the brightness of the epsilon ring is significantly enhanced at small phase and ring inclination angles, wich we attribute to an extreme opposition effect at ring inclination angles of ~1 deg. We further will discuss the zeta ring in detail; it appears to be vertically extended. We will address the potential ambiguities in our interpretation, caused by the fact that we cannot uniquely disentangle the single scattering albedo, optical depth, and phase function (the asymmetry parameter *g* in the Henyey-Greenstein scattering phase function).

Implications of Tidal Dissipation in the Inner Uranian Satellites

Rosemary Cave (Queen Mary, University of London)
and Craig Agnor

Uranus hosts a system of at least 13 small (R~10-80km) satellites orbiting near the planet (a ~ 1.9- 3.7 Ru). Dynamical scaling arguments and orbital integrations have shown that mutual gravitational interactions drive some of the inner uranian satellites to crossing orbits on timescales of 1e5, to 1e7 years - timescales remarkably shorter than the age of the solar system (Duncan & Lissauer, 1997 ; French & Showalter, 2012). Tides raised in satellites by the planet lead to damping of their eccentricities on a timescale that depends on their orbit and internal structure. Standard models of tidal dissipation that assume a satellite's interior is solid and monolithic suggest that the timescales to damp orbital eccentricity are much longer than those on which these satellites reach crossing orbits. However, if these satellites have interiors of rubble then their shapes may be more susceptible to deformation by tides and the global rate of tidal dissipation may be greatly enhanced by small scale granular friction. Using a simple model for tidal dissipation in rubble piles, scaling arguments and numerical simulations, we are investigating how tidal dissipation affects the orbital evolution of the inner uranian satellites. We will present our results and discuss the implications for the orbital history, structure and stability of the system, the interior structure of the moons and the nature of tidal dissipation within them.

Uranus satellites and rings : a close association

Sébastien Charnoz (AIM, Université Paris Diderot/CEA Saclay, France)

Uranus' rings structure are unique in the Solar System. Beside the fact that their composition is still unknown, a strange characteristics is that they seem very dynamics : ground-based observation since the 80's has revealed that their radial structure changes significantly over decades, a timescale that is surprisingly short for such objects. Beside this, they seem closely intertwinnned with nearby moons that have been suggested for long, to provide material to the rings at some times, and at some other times to take material from the rings. More recently it has been suggested that the rings themselves have given brith to the Uranus' moons.

I will present the main characteristics of Uranus' rings, as well as the main unknowns, and emphasize on the aspects related to their interaction with the satellites. I will illustrate how in-situe observation of Uranus' rings and moons may provide a much better understanding on the physical processes of rings and moons formation.

How to tilt the Uranus system while preserving its moons' equatorial orbits?

Aurélien Crida (Université Nice Sophia antipolis, Observatoire de la Côte d'Azur, CNRS, France)

I will present the results of a note published in 2012 by (Morbidelli, Tsiganis, Batygin, Crida & Gomes), in which we show that the existence of prograde equatorial satellites is consistent with a collisional tilting scenario for Uranus.
In fact, if the planet was surrounded by a proto-satellite disk at the time of the tilting and a massive ring of material was temporarily placed inside the Roche radius of the planet by the collision, the proto-satellite disk would have started to precess incoherently around the equator of the planet, up to a distance greater than that of Oberon. Collisional damping would then have collapsed it into a thin equatorial disk, from which the satellites eventually formed.
The fact that the orbits of the satellites are prograde requires Uranus to have had a non-negligible initial obliquity (comparable to that of Neptune) before it was finally tilted to 98°.

Dynamical insights into the history and composition of Uranus' rings and small moons

Matthew Tiscareno (Cornell University, USA)

The Uranus system has a sharp radial transition between an inner disruption-dominated region (containing dense rings) and an outer accretion-dominated region (containing moons). A characteristic density for transient clumps can be inferred from the Roche critical density (RCD) at the radial location of that transition, providing direct evidence that the material composing Uranus' rings is likely more rocky, as well as less porous, than the material composing Saturn's rings. The RCD is the minimum density of an orbiting object that, at a given distance from its planet, is able to hold itself together by self-gravity. We also point out that the "Portia group" of eight closely packed Uranian moons, whose orbits are so close together that they are not dynamically stable for more than 10 Myr, has an overall surface density similar to that of Saturn's A ring. Thus, although this assemblage of moons (along with the dusty Nu ring) has likely looked quite different over solar-system history, as moons are disrupted and re-accreted on a regular basis, it can be seen as an "accretion-dominated ring system," of similar character to the standard ring systems except that it is far enough from its planet that its material has a characteristic density greater than the local RCD.

Astrometric observations of the Uranian satellites

Jean-Eudes Arlot (IMCCE, Observatoire de Paris, France)

During the ring plane crossing in 2007, observations of the positions of the Uranian satellites have made possible thanks to specific events, the mutual occultations and eclipses of the satellites. The accuracy of the results is better that the one of the space probe Voyager 2 and will help for the dynamical study of the Uranian system.

Exploration of tidal dissipation in icy giant planets

Stéphane Mathis (Laboratoire AIM Paris-Saclay, CEA/DSM/IRFU/SAp, France), F. Remus, J.-P. Zahn, V. Lainey, S. Charnoz

Once a planet-satellite system is formed, tidal interactions strongly impact its dynamical evolution. By converting kinetic energy into heat, tides pertub their orbital and rotational properties. 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 such system, one has to identify the dissipative processes that achieve this conversion of energy. In this context, planetary systems display a large diversity of planets by their composition. Since tidal mechanism is closely related to the internal structure of the perturbed body, one has to investigate its effects on either its fluid and solid layers. Studies have been carried out on tidal effects in fluid bodies such as stars and envelopes of giant planets. However, the planetary solid regions may also contribute to tidal dissipation, be it the mantles of Earth-like planets that have been investigated by many works, or the rocky/icy cores of gaseous and icy giant planets. The purpose of our study is to explore the tidal dissipation in the solid central regions of icy giant planets, taking into account the presence of their fluid envelope. We derive the different Love numbers that describe the anelastic deformation and discuss the dependence of the tidal quality factor Q on the rheological parameters and the size of the solid central region. Taking plausible values for these parameters, and discussing the frequency-dependence of the solid dissipation, we show how this mechanism may compete with the dissipation in fluid layers, when applied to Uranus- and Neptune-like planets. Finally, we present the way to implement the results to study the dynamical evolution of icy giant planet-satellite systems.

Possible astrometric determination of tidal dissipation within Uranus from a future space mission

Valéry Lainey (IMCCE, Observatoire de Paris, France)

Tidal dissipation is the main actor of orbit migration among satellite systems. Recent work suggests possibly strong tidal dissipation within icy giant planets (Remus et al., 2013), with important consequences on satellite orbital evolution. Here we focus on the possible determination of tidal dissipation within Uranus using astrometric observations from ground and space. Besides regular observation campaigns from the Earth, simulations of observations from a future space probe around the Uranian system is considered. Constraints on the Uranian tidal ratio k2/Q as a function of astrometric accuracy and time span is assessed.

Session « Future observations and missions »

Uranus Pathfinder

Chris Arridge (Mullard Space Science Laboratory, University College London, UK)

Uranus Pathfinder is a mission concept proposed to ESA in response to its 2010 call for medium-class (M) missions. The mission proposed to explore the fundamental processes at work in the planet itself (its interior and atmosphere) and in its planetary environment (magnetosphere, satellites and rings). The mission would provide observations and measurements that are vital for understanding the origin and evolution of Uranus as an Ice Giant planet, providing a missing link between our Solar System and planets around other stars. Although ultimately unsuccessful in the medium-class mission call, Uranus Pathfinder attracted considerable international support and received very positive reviews. In this talk we discuss the Uranus Pathfinder mission concept, including science case and model payload, interplanetary transfers, thermal control, telemetry, radioisotope power source and science orbit.

The ODINUS Mission Concept

Diego Turrini (Istituto di Astrofisica e Planetologia Spaziali INAF-IAPS, Italy)

We present the scientific case and the mission concept for an L-class space mission to the ice giant planets Uranus and Neptune and their satellites with a pair of twin spacecrafts, and discuss its relevance to advance our understanding of these two systems so similar and yet so different, of the ancient past of the Solar System and, more generally, of how planetary systems form and evolve. The mission concept we illustrate will be referred to through the acronym ODINUS due to its main fields of scientific investigation : Origins, Dynamics and Interiors of Neptunian and Uranian Systems. The ODINUS mission concept is the subject of a white paper (accessible at the address http://odinus.iaps.inaf.it) submitted to ESA in response to the call for definition of the future L2 and L3 missions.

Heliospheric mission concepts submitted to the NASA decadal survey

Abigail Rymer (John Hopkins University Applied Physics Laboratory, USA)

A White Paper submitted to the Planetary Science Decadal Survey 2013-2023 (Hofstadter et al., 2009) provided a persuasive case for a Uranus orbiter to investigate the composition, structure, atmosphere and internal dynamo of the planet and the nature and stability of its moon and ring system. Subsequently two White Papers were submitted to the Heliophysics Decadal Survey for 2013-2023 (Hess et al., 2010 ; Rymer et al., 2010) providing powerful arguments for including a magnetospheric element in any future investigations of the Uranian system. One white paper presented the science case for a dedicated magnetospheric mission to Uranus, and the other presented a case for coordinating and/or combining the magnetospheric elements together with the proposed planetary orbiter. It was noted that the tour phases of these missions out to 20 AU afford rare opportunities to make solar wind observations in the outer heliosphere and as such appeal to an even broader section of the heliophysics community. Here I provide an overview of the Heliophysics White Papers that attempt to make the case for including a robust space environment element in any future missions to Uranus.

Uranus Orbiter and Probe Mission for the NASA Decadal Survey

Robert Gold (John Hopkins University Applied Physics Laboratory, USA)

A Uranus orbiter with probe mission was defined as part of the NASA Planetary Decadal Survey. The science goals of the Uranus mission are: 1) determine the planetary zonal winds and atmospheric composition, 2) understand the structure of the magnetosphere and the interior dynamo, 3) measure noble gas abundances and isotopic ratios, 4) determine the planet's internal mass distribution, 5) assess the thermal emissions, 6) measure magnetospheric fields and currents and their interaction with the solar wind, and 7) perform remote sensing observations of the large satellites. The realization of this mission includes a fully instrumented orbiter, a shallow atmospheric probe, and a solar-electric powered transfer stage to get the orbiter and probe to Uranus. The probe is released 29 days prior to orbit insertion and is tracked into the atmosphere to a depth of 5 Bars by the orbiter. The Uranus orbit insertion burn occurs shortly thereafter and it is the start of a roughly two-year primary science phase of the orbiter mission. The orbit is highly inclined to cover a wide range of magnetospheric latitudes and longitudes. The periapse is limited to >1.3 R_u to keep it outside of the ring system. Following the orbital science phase, the spacecraft will execute a series of maneuvers that will provide a total of 14 moon flybys of Miranda, Ariel, Umbriel, Titania, and Oberon. The closest approach for the targeted flybys is 50 km altitude. This mission concept is based almost entirely on existing technologies with only the large solar arrays and the Advanced Stirling Radioisotope Generators requiring further development. Following a 69-month development schedule, the mission would be launched on an Atlas V 531, or similar vehicle, with a total launch mass of 4129 kg. The cruise to Uranus takes 13 years. The total mission was priced at $1.7 billion in FY10 dollars.

Opportunites for joint US - european missions

Mark Hofstadter (Jet Propulsion Laboratory, California Institute of Technology, USA)

It is clear that the scientific community considers Ice Giants, and Uranus in particular, an important target for exploration. (See, for example, the recent U.S. Planetary Science Decadal Survey, the Heliophysics Survey, and associated White Papers.) It is not surprising, then, that mission proposals to both NASA and ESA have been made with new ones under development. Given budgetary pressures on all nations, international cooperation is a key factor in maximizing the science capabilities of smaller missions, and is likely to be required for a large, Cassini-class mission. Such a mission is ultimately what must be flown to do the science we want.

They key points I hope to make are that :
1) It is possible to do compelling science with missions in all cost categories. In each case, international cooperation has an important role.
2) There are mission proposals currently under development for the U.S. Discovery and ESA's L-Class programs which can benefit from your ideas and support.
3) The Cassini mission began many years ago with informal discussions between U.S. and European scientists. It is not too early to start thinking about what a Flagship Uranus mission would look like.

Session « Technical feasibility of a Uranus orbiter and probe »

European Space Nuclear Power Systems: Enabling Technology for Space Exploration Missions

Richard Ambrosi (University of Leicester, UK)

Radioisotope thermoelectric generator systems being developed in Europe are targeting the 10 W electric to 50 W electric power generation range adopting a modular scalable approach to the design. Radiogenic decay heat from radioisotopes would be converted to electrical power by using appropriate solid state thermoelectric materials. The plan for Europe is to develop radioisotope space nuclear power systems based on both thermoelectric and Stirling power conversion systems, with Stirling targeting 100 W power levels. The European radioisotope thermoelectric system development programme is targeting americium-241 as a fuel source and is maximizing the use of commercially available thermoelectric manufacturing processes in order to accelerate the development of power conversion systems. The use of americium provides an economic solution at high isotopic purity and is product of a separation process from stored plutonium produced during the reprocessing of civil nuclear fuel. Laboratory prototypes that use electrical heating as a substitute for the radioisotope have been developed in the UK and France to validate the designs. In this report, a UK perspective is provided on the requirements for the European Radioisotope Thermoelectric Generator (RTG), describes the most recent updates in system design and provides further insight into recent laboratory prototype test campaigns.

Recent Activities in ESA of Interest to the Exploration of Outer Planets

Frédéric Safa and Peter Falkner (European Space Agency, Future Missions Office, Science and Robotic Exploration Directorate, NL)

The presentation provides an overview of studies and technology developments recently achieved by the European Space Agency and of relevance to the exploration of Outer Planets beyond Jupiter. Mission scenarios to Saturn, Uranus and Neptune will be briefly discussed as well as selected technology developments, in particular on power sources for space applications.

The concept of electrical sailing

Pekka Janhunen (Finnish Meteorological Institute, Finland)

The solar wind electric sail (electric sail, E-sail) is a novel deep-space propulsion method which was invented in 2006 and which is under development in Europe. The E-sail is a spin-off invention of basic space plasma physics research and uses the solar wind dynamic pressure to produce spacecraft propulsion. The E-sail consists of long, thin and artificially charged metallic tethers which are centrifugally stretched. The electric field of the charged tethers penetrates several Debye lengths into the surrounding solar wind plasma which causes deflection of the solar wind protons, thereby tapping momentum from the solar wind flow to the tethers and the spacecraft. The main benefit of the E-sail is high efficiency (large total impulse per propulsion system mass: as much as 50-500 times larger than ion engines and chemical rockets), propellantless nature and good controllability (e.g., the E-sail can be turned off at any time by turning off the electron gun which maintains the charging of the tethers). The E-sail's thrust scales as 1/r where r is the solar distance - this peculiar scaling law comes from the combined effect of the scaling of the Debye length and the solar wind dynamic pressure. Thus the E-sail is particularly well suited for outer solar system missions. Presently, E-sail hardware (scalable up to 1 N of thrust at 1 au) is at TRL 4-5, including successful production of 1 km long tether and a Remote Unit prototype which passed environmental testing. The first CubeSat test mission ESTCube-1 which carries a 10 m long E-sail tether was launched successfully in May 2013. From ESTCube-1 which is now in early operations phase, we are hoping to get E-sail effect measurement data in August/September 2013. We think that the E-sail is a paradigm shifting technology for advanced solar system exploration whose development has proceeded rapidly and no significant obstacles or problem areas are known which would prevent construction of large E-sails suitable for challenging missions.

Uranus and Neptune : ice giants one launch away

Sini Merikallio (Finnish Meteorological Institute, Finland),
P. Janhunen, M. Paton, P. Toivanen, J. Envall, J.-P. Lebreton

The Electric Solar Wind Sail technology provides the means to reach outer planets in a reasonable time, with a flexible launch window and low cost. This new propulsion method uses long (20 km) and thin tethers charged to high voltages (~20 kV) to convert the momentum of the solar wind particles into spacecraft thrust (Janhunen et al., 2010). Contrary to traditional photonic solar sails and solar power, which both scale as 1/r2, the E-sail thrust scales as 1/r, r being the distance to the Sun, which further increases E-sails appeal for outer solar system exploration. The technology is being developed in an FP7 project ESAIL, http://www.electric-sailing.fi/fp7 and currently tested onboard ESTCube1, which was successfully launched on May 2013. Here we take a look at the

possibilities and feasibility of an ice giant mission realised with the E-sail propulsion.

E-sail, once in the Solar Wind, can be steered continuously after launch, making it possible to send probes to several different destinations on a same launch. In essence, the continuous, steerable acceleration does not require planetary fly-bys and is relatively free of launch window constraints. Moreover, low spacecraft mass due to the absence of fuel tanks leads to low costs, and as a similar design can be implemented on both Uranus and Neptune probes, also the manufacture and assembly costs are greatly reduced.

As an example, with a standard E-sail (1 N thrust at the 1 AU distance from the Sun), Neptune could be reached in five years with 500 kg of payload. Payload here stands for the whole spacecraft mass from which the mass of an E-sail has been subtracted. Delivering 1000 kg would take 8 years and could be launched anytime, without needing to wait for a suitable launch window. Travel times with E-sail to the ice giants are tabulated in Table 1 for 500 and 1000 kg payloads.

Entry probes have been proven to be possible with entry speeds as high as 47 km/s (Galileo in Jupiter, 1995), which makes them very good combination with E-sail probes with entry speeds less than 30 km/s for both Uranus and Neptune.

If an orbiter mission would be considered, orbital insertion would be somewhat challenging due to the relative low masses of the ice giants and the fast approach velocity of the E-sail propelled spacecraft. Traditional chemical engines will be unable to provide the required impulse for orbit insertion and aerocapture technologies are needed. Presently available solutions, without E-sail, would require a large spacecraft due to massive amounts of the fuel needed. Moreover, they would require dedicated launches, most likely one separate for both of the planets within a very time-constrained launch window.

Target planet	Payload weight	Travel time
Uranus	500 kg	3.1 yr.
	1000 kg	5.3 yr.
Neptune	500 kg	4.6 yr.
	1000 kg	8.0 yr.

Table 1. Travel times to Ice-giants

Relatively light-weight and high payload ratio vehicles enabled by the E-sail could, on the contrary, piggyback on any launch taking them to the escape orbit so that they could unwind their tethers and start sailing on the solar wind. The E-sail thus has the potential to change the trend of dedicated launches and to enable low-cost small and moderate mass planetary probes to the outer planets that can be launched in arbitrary mixed combinations with any Earth-escape-capable launcher to any outer solar system targets, Uranus or Neptune, but also Jupiter and Saturn.

Session « Past datasets and coming observations »

Back to the future I : Access to Voyager 2 multi-instrument magnetospheric and plasma datasets through the CDPP AMDA and 3DView Tools

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IRAP and CDPP (French Center for Space Physics Data, http://cdpp.cesr.fr/) have a long and internationally well-recognized experience in developing sophisticated and modern analysis tools with innovative and advanced functionalities for space plasma data.
These last years a particular attention has been given at IRAP and CDPP for the preparation of future missions to the outer planets. The developed tools and associated databases are now opened to the broad scientific community in order to enable an in-depth re-analysis of previously underexploited multi-instrument datasets.
The CDPP/AMDA (Automated Multi-Dataset Analysis) tool provides advanced functionalities for performing automated search of events, producing time tables and catalogues, as well as basic data treatment (formatting, bad point filtering, re-sampling, data merging, scatter plot) in order to provide to the user data ready to use with her/his favourite software. A complete database with all existing magnetospheric-related Voyager 2 data for the Uranus flyby (magnetic field, plasma, energetic particles, waves) has been built in AMDA. In addition this database is directly connected in an interoperable way to HST observations of giant planet auroral emissions and the Aladin tool, based on the SAMP protocol.
The Voyager 2 mission trajectory and ephemerids have also been added to 3DView/CDPP, a tool for scientists that offers immediate 3D visualization of position and orientation of spacecraft, planetary ephemeris, as well as scientific data representation. We will illustrate the scientific benefits of our added value services in the context of past and future exploration of Uranus.

Back to the future II : Accessing HST auroral observations through the APIS database

Laurent Lamy (LESIA, Observatoire de Paris, CNRS, France)

Remote UV measurement of the outer planets are a wealth of informations on rings, moons, planetary atmospheres and magnetospheres. Auroral emissions in particular provide highly valuable constraints on the auroral processes at work and the underlying coupling between the solar wind, the magnetosphere, the ionosphere and the moons. Key observables provided by high resolution spectro-imaging include the spatial topology and the dynamics of active magnetic field lines, the radiated and the precipitated powers or the energy of precipitating particles.

The Hubble Space Telescope (HST) acquired thousands of Far-UV spectra and images of the aurorae of Jupiter, Saturn and Uranus since 1993, feeding in numerous magnetospheric studies. But their use remains generally limited, owing to the difficulty to access and use raw and value-added data.

APIS, the egyptian god of fertilization, is also the acronym of a new database (Auroral Planetary Imaging and Spectroscopy), aimed at facilitating the use of HST planetary auroral observations. APIS is based at the Virtual Observatory (VO) of Paris and provides a free and interactive access to a variety of high level data through a simple research interface and standard VO tools. We will present the capabilities of APIS and illustrate them with several examples : http://lesia.obspm.fr/apis

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Back to the future III : Uranus Datasets in Virtual Observatory Tools

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In the frame of the Europlanet EU-FP7 project, the infrastructure of a planetary sciences virtual observatory (VO) was set. It is based on existing international standards, as defined by the International Virtual Observatory Alliance (IVOA), with adaptations to the planetary sciences. We present a series of tools that facilitates the access to datasets and allows easy display observation as the adopted standards allow the user to use existing VO display tools, developed initially for astrophysical data.

Session « Instrumentation suitable to a Uranus mission »

Radio Science Investigations at Uranus

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Radio science investigations fall into three broad categories: propagation, bistatic radar and gravity. The Radio Science experiment employs radio occultation to (i) sound the neutral atmosphere of Uranus to derive vertical density, pressure and temperature profiles (ii) sound the ionosphere to derive vertical ionospheric electron density profiles and a description of the ionosphere through its diurnal and seasonal variations with solar wind conditions; (iii) determine the dielectric and scattering properties of the surface of Uranus in target areas , the dusty rings and Uranus moons by a bistatic radar experiment, (iv) determine the gravity field of Uranus and its moons to derive information about the internal structure.

The Radio Science investigation relies on the observation of the phase, amplitude, polarisation and propagation times of radio signals transmitted from the spacecraft and received with antennas on Earth. The radio signals are affected by the medium through which they propagate (atmospheres, ionospheres, interplanetary medium, solar corona), by the gravitational influence of the planet on the spacecraft and, finally, by the performances of the various systems aboard the spacecraft and on Earth.

Simultaneous and coherent dual-frequency downlinks at X-band (8.4 GHz) and Ka-band (32 GHz) via the High Gain Antenna permits separation of contributions from the classical Doppler shift and the dispersive media effects caused by the motion of the spacecraft with respect to the Earth and the propagation of the signals through the dispersive media, respectively.

The Radio Science experiment makes use of the radio link between the orbiter and the ground station(s) on Earth. An Ultrastable Oscillator (USO) serves as a highly stable frequency reference source for operations in the one-way radio link mode to be applied during atmospheric/ionospheric sounding, gravity measurements and bistatic radar observations at Uranus moons.

The One-way radio link is proposed in order to minimize tracking problems caused by the extreme light travel time and carrier frequency variations due to strong ray bending in thick atmospheres.

The experiment can be realized as an uplink or as a downlink experiment. In the first case a ground station transmits the carrier signal and while in the second case it is the spacecraft which transmits the carrier signal.

An optional DPS unit allows to analyze Radio Science data onboard and to transmit the frequency residuals as part of the regular TM data stream.

Unveiling the evolution and formation of icy giants

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Introduction : The Austrian Space Agency in colaboration with ESA holds a 2-week summer school every year for graduate students and young professionals to design a mission of their choice within that year's theme in Alpbach, Austria. This paper presents the outcome of the 2012 edition, with the theme 'Exploration of the giant planets and their systems'. The planet Uranus is one of two ice giants in the solar system, both of which have only been visited only once by the Voyager 2 spacecraft. Therefore, a dedicated mission to an ice giant is crucial to deepen our knowledge of the formation, evolution and current characteristics of such a planet and its system. We present the science objectives, architecture rationale and system design for a mission to the Uranian system. We conducted a detailed study on how to best fulfill the primary science goal, namely : to investigate Uranus and its system as an archetype for ice giants. To this end, we formulated specific science questions leading to measurement requirements and, finally, in- strument requirements and suitable instruments.
The primary science questions relate to investigating Uranus' deep interior and outer layers as these are directly related to the primary science goal. Additionally, investigations of the moons, rings and the magne- tosphere will provide complementary observations of the Uranian system specifically and icy giants in general.
Method : A trade-off between several mission architectures was performed, such as an orbiter with an atmospheric entry probe and a flyby mission. In this process, the relative importance of the science questions, the capabilities of each concept to carry a certain payload and its capability to answer the science questions in the given architecture were traded off. Similar- ly, the feasibility of each concept from an engineering point-of-view was assessed, taking into account matters such as complexity, cost and risk. The results are presented as a function of relative engineering and science score weights, providing an envelope of optimal mission selections over a range of mission scenarios. We conclude that a Uranus orbiter with a single entry probe and an extended moon tour fulfills the primary science goal in an optimal manner.
Outcome : The chosen mission scenario is based on a launch date in 2026 on an Ariane 5 ECA launcher and arrival at Uranus in 2044 using conventional high-thrust systems. The first two years of the mission are dedicated to observations of Uranus. In this phase, the periapsis is very close to Uranus and the apoapsis is outside the bow shock, specifically for performing magnetospheric studies. Subsequently, the periapsis is raised allowing for a nominal nine flybys for each of Uranus' largest moons. Dry mass in

Uranus orbit is 2052 kg taking into account both system and subsys- tem margins. The probe's mass (350 kg), however, is not included. The spacecraft will be powered by four ASRGs which are currently under development. A set of batteries is included, capable of covering the loss of one ASRG through the peak power phase. It will have ~100 Gbit data storage capacity for optimizing the science return through careful selection of transmitted data. Data transmission is performed by a 3.5 m high gain antenna transmitting in X-band for communica- tions and Ka-band for tracking. Possibilities exist for mission extension at the final orbit, which crosses the orbit of the moon Oberon, to extend even further the science return about this ice giant from this mission.

Energetic Neutral Particles in the Uranian system

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Neutral particles do not interact with electromagnetic fields, hence, if their energies are high enough to overcome the planet's gravity and if collisions with other neutral or charged particles are negligible, their characteristics are maintained unchanged through time. Due to this property, information about the (remote) neutral generation process can be obtained through Energetic Neutral Atoms (ENA) detection. This powerful tool has been applied in the Earth's environment for imaging the magnetospheric plasma circulation through the detection of charge exchange ENA (c-e ENA) in the energy range 1-100 keV. C-e ENA have been detected also in the solar wind (neutral solar wind) in the energy range 500-3000 eV and in many planetary environments like Mars, Jupiter, Saturn and Titan in the energy range 1-100 keV. The outstanding science related to these observations deals with global plasma circulation and dynamics, interaction between magnetospheric plasma and neutral gas (moon exospheres and gas tori). Recently the energetic neutral atoms (at energies < 1keV) have been detected also from the Moon's surface. These particles are generated mainly by the back scattering of solar wind protons that flow in the flank of the biggest magnetic anomalies impacting the surface of the Moon. Even if never observed for technological limitations, Energetic Neutral Particles (ENP) are generated also at lower energies (10-500 eV) by other processes like surface and atmosphere ion-sputtering, during plasma interaction with solid surfaces and dense atmospheres, respectively. Instruments able to image these processes will be operated in the Mercury's environment during the upcoming BepiColombo mission. In this case a detailed study of the Sun-planet interaction processes will be feasible.
In the context of a future space mission to Uranus, the Energetic Neutral Particle (ENP) detection in the diverse energy ranges will permit the investigation of the interaction between the planet's magnetosphere, exosphere and moons environments, determining the plasma dynamics, the atmospheric escape, the icy moons' surface erosion as well as the energy balance in the whole ice giant system. In fact, in the Uranus' system c-e

ENA (tens of keV) are generated by the interaction of the moon tori with the magnetospheric plasma. The possibility to perform c-e ENA imaging during the s/c apoapsis phases is the only way to study global plasma dynamics for a long period. During close approach to the planet's auroral zones both c-e ENA and atmospheric sputtered particles (ENP in the energy range: 0.5- few keVs) can be imaged in order to investigate the plasma-planet interactions. During icy moons flybys, the backscattered and surface ion-sputtered particles (ENP in the energy range: 10s eV – few keVs) can be detected in order to investigate the interaction between the plasma and the icy moons' surfaces. The overall goal of the current proposed study is to address the second and the third scientific theme of the Cosmic Vision 2015-2025 program, i.e.: "How does the Solar System work?" and "What are the fundamental physical laws of the Universe?".

Energetic Particles at Uranus

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The single flyby of Uranus by Voyager 2 in 1986 established that the uranian magnetosphere is a highly dynamical system that has both proton and electron radiation belts. Of all the planets, Uranus has an extremely unique configuration of its rotation and magnetic axis. The parameters of the solar wind interaction (time scale for changes in geometry, geometric extremes, solar wind density and magnetic field strength, etc.) are so unlike those at Earth, that the range of behaviors exhibited by Uranus' trapped ion and electron populations cannot be accurately modeled or predicted. From Voyager 2 we know Uranus to have fairly intense trapped electron radiation belts (for energies 1 MeV and below, comparable to Earth's at their most intense), as well as a considerably less intense trapped ion population. The Uranian magnetosphere was also discovered to be very dynamic, exhibiting ion and electron injections in the 10's to 100's of keV similar to those found in Earth's magnetotail and ring current. At Earth, energetic ions are thought to be accelerated through reconnection processes in the magnetotail. However, it is not known how such process operates at Uranus with its unique magnetic dipole orientation, making Uranus an environment of prime interest to the heliophysics and planetary magnetopheres communities. Understanding these processes at Uranus are important not only for understanding fundamental particle acceleration in planetary environments, but also for beginning to understand the vastly varying environments encountered at exoplanets. As in the cases of the other outer planet flagship missions to date, the multi-disciplinary nature of a potential Uranus mission makes the inclusion of an energetic particle measurement capability of paramount importance.

In recent years, we have developed two novel energetic particle sensors very well suited to measurements at Uranus, the 2π coverage ion composition sensor currently in Phase

B for flight on Solar Probe Plus (EPI-Lo, affectionately known as the "mushroom"), and the fan aperture, magnetically swept electron sensor recently selected for the JUICE Mission, JoEE, known also as the electron pie. The two together (mushroom pie) will make a well suited pair for measuring the energetic ion and electron environment at Uranus, including ion composition and detailed ion and electron angular distributions.

Infrared spectro-imaging: a key technique for the atmospheric investigation of Uranus and Neptune

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and the IAPS planetary sciences team

The capability of coupling imaging and spectroscopy in the infrared range has demonstrated as a powerful technique for investigation of the planetary atmospheres, in terrestrial (VIRTIS-Venus Express, OMEGA-Mars Express) as well as gaseous giant (NIMS-Galileo, VIMS-CASSINI) planets. We review here the potential of spectro-imagers in atmospheric science for possible future missions to Uranus and Neptune. Accurate mapping of VIS/IR albedo - at different spatial and temporal scales and wide spectral range - is fundamental to determine the actual solar energy input to the icy giants and eventually their actual heat balance.
The substantial content of methane in the atmospheres of Uranus and Neptune and the wide absorption bands of this compound allow to probe the atmosphere in a range of altitudes, and to characterize the vertical aerosoldistribution. This capability is best exploited in conjunction with imaging, allowing to monitor the dynamics by cloud tracking and aerosol properties by the study of their scattering phase function and spectral shapes.
Determination of the content of other minor species (water, ammonia, phosphine) is also possible exploiting the methane spectral transparency windows. While the retrieval of their bulk contents is precluded to IR investigation by the clouds, nonetheless, key information can be gathered about the vertical motions (using minor gases as tracers) as well as about deeper levels, in areas of local aerosol clearance (e.g. Neptune Dark Spots).
The conditions in the stratosphere of Icy Giants can be constrained by means of limb IR observations of non-LTE emissions (by methane-chemistry products) and star occultation measurements.

The unique configuration of Uranus magnetosphere determines a complex interaction between the interplanetary environment and the thermospheres of Icy Giants. The auroral phenomenology could be effectively monitored, including determination of altitudes and rotational temperatures, by observations of infrared H3+ emissions, complementing the data of the UV spectrometers and ENA imagers.

Composition and origins of the Uranian moons by imaging spectroscopy

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The albedos of the five major satellites of Uranus, varying between 0.21 e 0.39, are considerably lower than those of Saturn's moons (except Phoebe and the dark hemisphere of Iapetus). This reveals that water ice, which dominates their surfaces, is mixed in varying proportions with other non-icy and visually dark materials.

Due to the absence of a near infrared spectrometer onboard Voyager 2, no detailed information about the surface chemistry of the Uranian moons is available. Just to give a few examples, there is no indication about the chemistry of the structural provinces identified on the surfaces of Titania and Oberon, exhibiting different albedos and different crater density that reveal different ages. Similarly, unknown is the nature of dark material (perhaps rich in organics) that fills the floors of major impact craters on Oberon, as well as the composition of the annulus of bright material that is enclosed in the large Wunda crater on Umbriel. The chemical nature of the flows of viscous material observed on Ariel and Titania is also unknown. Moreover, a clear indication of the presence of ammonia hydrate on the surface of Miranda, suggested by Bauer et al. (2002) on the basis of telescopic observations, is lacking.

By using an imaging spectrometer in the near infrared range from 0.8 mm to at least 5 mm, it will be possible to unveil the surface composition of the moons by identifying and mapping various chemical species (with particular emphasis on non-water ice materials, including volatiles and organics). This will ultimately enable an unprecedented correlation of surface composition with geologic units at various spatial scales.

Spatially resolved chemical mapping should be compared on one side with the geological information provided by optical cameras, and on the other side with energetic neutral particle and plasma measurements that could provide a mapping of the radiolytic and sputtering processes, indicating the regions of major exogenic activity. Joint spectroscopic, geologic and particle measurements, therefore, could provide important information on the role of processes that lead to the exchange of material between the surface and the subsurface as well as of those responsible for the exogenic activity.

In addition, a comprehensive exploration of the Uranian moon system is necessary to study these objects through a comparative approach which shall allow us: 1) to trace the radial distribution of surface icy and non-icy (chromophores) materials at different radial distances from the planet; 2) to correlate surface composition with bulk composition of each satellite, and 3) to better constrain the rock/ice ratio and composition necessary to discriminate among the different formation models (Pollack et al., 1991).

In a broader perspective, surface composition as inferred from imaging spectroscopy can help us in gather an understanding of the relationship occurring between the formation of the Uranian moons and the origin of the planet. The regular moons of Uranus are believed to have formed in the accretion disc, which existed for some time after its formation or resulted from the large impact suffered by the planet early in its history. Chemistry of the regular satellites of the giant planets can be directly related to a physical process similar to the one that, at a larger scale, led to the formation of the planets themselves. The evolution of geochemical processes in the satellites can be constrained by measuring the detailed distribution of volatile and organic compounds. Combining the information that can be derived through the use of near-infrared spectroscopy with data returned by mass spectrometry and information about density and internal structure that is inferred from radio science data can ultimately provide a 'big picture' regarding the formation of these bodies.

Radio emissions from Uranus "de près et de loin"

Philippe Zarka (LESIA, Observatoire de Paris, CNRS, France),
Laurent Lamy et al.

Voyager 2 discovered in 1986 a rich zoo of Uranian radio emissions, from both hemispheres, smooth or bursty, on O or X modes. Magnetospheric radio emission cover the range ~1 kHz - 1 MHz, whereas atmospheric lightning-associated radio emissions were detected up to 40 MHz. While dominant magnetospheric radio components are likely due to the now classical cyclotron Maser instability, numerous open questions include the location of their sources, their relation to magnetospheric dynamics (including Solar Wind and satellite control), an explanation of their time-frequency morphology, their correspondence to other planetary radio emissions, their relation to UV aurora and magnetic topology, ...
We will review our present knwoledge of the subject, recent attemps to detect Uranian lightning from the ground, prospects for observation of Uranus' magnetospheric radio emissions from the Moon, as well as the basic characteristics of a radio instrument on the next space mission that will revisit Uranus.