General conclusions

Dear colleagues,

The conference *Uranus beyond Voyager 2, from recent advances to future missions* was held at the Observatory of Paris (Meudon, France) from 16 to 18 Sept. 2013. The audience was composed of about 90 scientists and engineers from 12 countries, interested in the study of this unique planetary system. The purpose of the meeting was twofold:

(i) Review our current knowledge of this astrophysical object and identify the key science questions;
(ii) Summarise the required measurements to address these, and assess the need for a dedicated space mission and complementary Earth-based observations.

The presentations, distributed in 10 science sessions, demonstrated a large, diverse and enthusiastic interest of our community for this target within the planetology, heliospheric and astrophysical fields. The detailed program, abstracts, and list of participants are available on the webpage: http://uranus.sciencesconf.org

The discussions ending each of the sessions in particular, and the conference in general, yielded a series of conclusions and recommendations, which are summarized below.

(i) Uranus remains the most puzzling planet of the solar system, characterized by a large obliquity (98°), a large tilt between its rotation and magnetic axis (59°), a low thermal heat and intermittent atmospheric activity, an asymmetrical magnetosphere and a complex collection of rings and prograde satellites. Uranus, along with Neptune, forms a unique and under-explored category of planets within our solar system (the so-called ice giants) and, in turn, is a tracer of the story of our solar system. Moreover, as ice-giant-sized objects appear to be commonplace among the ensemble of planets in our galaxy, Uranus may provide a relevant template for our interpretation of this class of extrasolar planets. Overall, Uranus provides an *in situ* laboratory for investigating numerous physical processes of broad astrophysical significance.

Although briefly explored during the *Voyager 2* flyby in 1986 (with a spacecraft launched 36 years ago) and remotely observed with discontinuous Earth-based measurements since then, Uranus remains poorly understood. It yields far more *basic* questions than answers with respect to the other planets, such as:

- What processes and characteristics define Uranus as an archetype of ice giants?
  (e.g. formation and evolution, internal structure, magnetic dynamo)
- What is the origin of Uranus' unique features? How and why does it differ from Neptune?
  (e.g. obliquity and hemispheric seasonal forcing, magnetic tilt, non-adiabatic interior, atmospheric, magnetospheric and rings/moons dynamics)
- What does Uranus reveal about our solar system? About the diversity of exoplanets?

(e.g. composition and constraints on the proto-solar disc, hot thermosphere, unique radio emissions and magnetosphere, outer heliosphere)

A more exhaustive list of questions is detailed per science topic in the appendices below.

(ii) The scientific and instrumental presentations made clear that Uranus is a top-level priority for several scientific fields. Its extreme planetary, magnetospheric, and heliospheric environments will bring 'L-class' science return in our understanding of fundamental processes operating in our Solar System and beyond. The crucial measurements needed to achieve the study of this system deserve an ambitious space mission, supported by complementary Earth-based observations.

With the exception of Neptune, located twice as far away, Uranus remains the only planet not explored by a dedicated orbiting spacecraft. It thus stands as the next step for exploring the solar system, as witnessed by numerous Uranus mission concepts recently proposed to NASA, ESA and CNES calls. As a community, we strongly support a mission toward Uranus, for which we highly recommend:

- A spacecraft to be planned within the 2020-2030 decade, operating along an orbital tour designed to adequately sample the Uranian environment, with short polar orbits and repeated flybys of the main moons (*especially Miranda and Ariel*);
- An atmospheric probe and/or aerocapture trajectory to complement remote sensing with *in situ* measurements;
- and an instrumental payload adequate to fulfill the above key science objectives.

Immediate next steps require:

- Feasibility studies to retire risks and develop required technologies for such a mission *(phase 0 studies, power supplies such as Radioiosotope Thermoelectric Generators, propulsions modes, optimization of heliospheric measurements during the cruise phase, improved data compression techniques, optimization of telemetry …)* ;
- An examination of useful collaborations between national and international space agencies (*in particular, lay the groundwork for a multi-agency, Cassini-class Uranus orbiter*).

In parallel, we highly recommend the pursuit of Earth- and space-based long-term observations of Uranus from equinox to solstice with existing or coming facilities, in parallel to modeling efforts. We encourage in particular:

- Multi-spectral remote sensing observations from the UV to the microwave to study Uranus' atmospheric structure, composition, clouds and chemistry as well as the dynamics of the satellites and rings' system;
- Investigations of the magnetosphere with UV observations and of its coupling with the ionosphere via auroral activity and heating through IR measurements;
- aLow frequency radio observations to detect Uranian atmospheric lightning, radiation belts (ground-based) or auroral emissions (space-based);
- Simulations and modeling necessary to tackle the science questions listed above.

Very sincerely,

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Appendix : Interior and Origins

The main questions regarding Uranus' interior have been summarized as follows.

(1) Origins:
- How did Uranus get its tilt?
- Where did Uranus form? Do the planetesimals that went into it originate from the same region?
- What stopped the growth of Uranus?
- How similar are Uranus and Neptune?

Addressing these questions requires measurements of noble gases and isotopic ratios.

(2) Interior:
- What is the internal structure of Uranus?

Requires gravity measurements (either directly from spacecraft tracking or from observations of ring precession) and Doppler Seismology.
- Uranus' low internal heat release : is the interior adiabatic?

Requires improved measurements of the heat flux and interior density profile.
- How can uranian interior models connect to planetary formation models? Explain dynamo generation, atmospheric dynamics etc. ?

Requires measurements of (Noble gases, 14N/15N, 12C/13C, D/H and C, O, S, N, P) on Uranus, together with (Ar, Kr, and Xe) in comets and an improved knowledge of the equation of state and mixing behavior of ices/rocks/gas at high pressure and modeling of dynamo/interior.

Most of these requirements can only be reached by close observations and in situ atmospheric sampling from a dedicated space mission.

Appendix : Magnetic field and Magnetosphere

Uranus' magnetic field and associated magnetosphere yield the following questions.

(1) Internal field and planetary dynamo:
- What is the configuration of Uranus' internal magnetic field? Did it undergo a secular change since Voyager 2?

Requires magnetic field measurements over a wide range of longitudes and latitudes at low (<2 R_U) altitudes to constrain magnetic field models to at least degree 8. Spatial and temporal sampling is also needed to characterize the external (magnetospheric) magnetic field.
- What is the connection between internal heat flux and dynamo generation?

(2) Magnetosphere:
- What is the configuration of Uranus' magnetosphere? How does it vary with season? With solar cycle?
- What are the main sources and sinks of plasma near equinox? Do they vary with time?

- What drives the dynamics of the Uranian magnetosphere? What is the internal rotation rate?
- What is the nature and variability of the coupling between the solar wind, the magnetosphere and the ionosphere?
- How are the icy satellites do interact with the magnetosphere?
- Where are localized the main auroral emissions? What is the specificity of ice giants radio emissions?
- What are the physical processes that drive Uranus' radiation belts with extreme tilt and offset of the magnetic field?

Addressing these questions require a set of spacecraft observations including in situ measurement of magnetic field, plasma and radio and plasma wave emissions, remote auroral spectro-imaging at UV, radio and IR wavelengths and observations of energetic neutral particles over a range of positions (e.g. scanning all latitudes and longitudes, inside/outside the magnetosphere, within auroral radio sources) and seasons. Multi-point measurements over wide spatial scales would be unvaluable.

Most of these requirements can only be reached by close observations and in situ magnetospheric sampling from a dedicated space mission.

Appendix : Atmosphere and Ionosphere

The main questions dealing with Uranus' atmosphere have been divided into three categories.

(1) Circulation and Dynamics:

- What powers the circulation, dynamics, meteorology, and evolution of Uranus?
- Why does Uranus differ from Neptune? Which is the archetype ice giant and why?
- What causes the differences in banding, zonal winds and cloud activity between ice and gas giants?
- How is Uranian 'weather' related to the deep interior, and how deep do the winds/plumes/vortices extend?
- How does Uranian 'weather' propagate up through the atmosphere and does it ultimately interact with the magnetosphere?
- What is the balance between intrinsic luminosity and sunlight?
- What is the seasonal dependence of insolation & energy emission, both horizontal and vertical: phase lag, temperature, and activity?
- What are the long-term (multi-decadal) processes that drive atmospheric and thermopsheric change (global climate)?

Ground- and space-based observations at UV, visible, IR, and radio wavelengths, along with space-based measurements of the gravity and magnetic fields, are needed. Future efforts should correlate changes to cloud albedo, winds, eddies and vortices with environmental processes (e.g. latent heat from condensation, meridional overturning, seasonal variability, etc.) to understand the processes controlling the changing face of Uranus and to compare with the other giants.

Long term, continuous 'time-domain science' will be required, tuned to the timescales of interesting phenomena.

(2) Composition and chemistry:
- What is the origin of the zoo of chemical species that make up Uranus?
- Are elemental abundances (C, He, O, N, S, P, Noble gases) and isotopic ratios (^{13}C, ^{15}N, ^{18}O,s D/H) consistent with planetary formation hypotheses?
- How does upper atmospheric chemistry vary globally and with temporal/seasonal/external forcing?
- Why/how does this differ from the other giants?
- Are deep atmospheric features seen at radio wavelengths controlled by thermal or chemical processes?
- What is the distribution of cloud-forming volatiles (esp. CH_4), disequilibrium species, and photochemical products?
- What does upper atmospheric chemistry tell us about the external supply (comets, micrometeoroids, connection to satellites/rings) of material to Uranus? What about a giant impact in the past?
- What is driving changes in the thermosphere/ionosphere: interaction with the atmosphere, or rings, or moons? Can the thermosphere be used as a probe of the rings and magnetosphere?

High spatial and spectral resolution imaging, primarily at IR to radio wavelengths, is needed to map the distribution of chemical species in Uranus' atmosphere and monitor their temporal variability.

(3) Structure and clouds:
- What determines the vertical structure, clouds and energy transfer mechanisms from the deep interior to the upper atmosphere/thermosphere? What drives zonal variability?
- What are the principle constituents of the cloud decks; does a deep H_2O cloud exist?
- What is the depth of the weather layer?
- What determines the spatial and temporal variability of discrete cloud features, and how do discrete features relate to environmental variations (temperature, pressure) and compositional variations?
- How is internal energy transported from the interior, through the weather layer and into the upper atmosphere (i.e. what is the importance of convection and waves?)?

Multi-wavelength spectro-imaging analyses are needed to probe the vertical structure of the atmosphere and relate it to (i) the interior and (ii) the tenuous ionosphere/thermosphere. Gravity and Doppler Imaging measurements from a spacecraft would also complement these studies.

Appendix : Rings and moons

The objectives in this field are twofold.

(1) Moons:
- What does the unseen ~60% of the major moons look like? Do they possess any activity? Atmosphere? Internal ocean?
- Have past or present tidal interactions between moons driven internal activity? When and why and how have Miranda and Ariel been active? Are they active now? What is the origin of their coronae and canyons?
- Why do the moons show hemispheric variation in water ice absorption bands?
- Do dark patches on Oberon and other moons indicate cryovolcanism?
- Are the moons differentiated? What are their gravity characteristics?
- Do (or did) the moons contain subsurface oceans? What are their electromagnetic characteristics?
- Do the moons demonstrate any non-synchronous rotation?
- Can moon composition be determined from direct analysis of ejected dust?
- What is the composition of the moon surfaces, interiors? What is the "dark material"? What are the color and brightness variations and what causes them? How have the surfaces been affected by irradiation, by dust?
- How and why is CO_2 ice distributed within and among the moons? What is the source of C?
- Can models of orbital/tidal/thermal history (constrained by relevant data) explain observed moon activity?
- Better characterize the complex interaction among the inner moons and the magnetosphere and understand origins and future of the system

(2) Rings system:
- What is the origin of temporal variation in the orbit of Mab, and of the structure of the Mu ring? Moonlets in the ring?
- What is the structure, composition and variability of the dusty rings?

The gravity harmonics of Uranus, especially J4, are known most sensitively not by s/c tracking, but by observing ring precession.
- What are the particle properties of the Lambda ring?
- What are the spatial and temporal characteristics of the Zeta ring? Is there any chance that proximal orbits might be determined safe after some reconnaissance?
- What are the sizes, shapes, interior structure of the small inner moons? Might they affect mid- or long-term stability?
- Can better observations of the Uranus system better constrain the origin of the tilt or of the moon system?
- How do the rings interact with magnetosphere?

Earth-based measurements at visible and IR wavelengths can address some of these compositional and dynamical questions, but a spacecraft orbital tour is critical for most of them.

A minimum of two flybys is needed for each investigated moon. Priority should be given to repeated flybys of the primary targets of interest identified during the meeting : Miranda and Ariel for geological studies, Ariel and Titania for geophysical studies.

High-fidelity optical remote sensing are important. The longer time baseline of an orbiter is valuable for addressing many questions, including more accurate precession rates. Both stellar and radio occultations of the rings are valuable for high-fidelity investigations of ring structure, and can also probe particle sizes and compositions. Definitive chemical analysis of faint-ring *composition can be determined by in situ sampling of dust and plasma while their interaction can be investigated through remote sensing of energetic neutral particles.*

Appendix : Science case for an interplanetary cruise phase in the outer heliosphere

The essential science themes to investigate along the cruise phase of a spacecraft enroute for the outer heliosphere have been divided into three axis.

(1) General relativity:

- Is the general relativity theory valid? Can a deviation observed from the predicted universe acceleration help us to unify the four fundamental forces? And/or provide hints on the nature of dark matter and dark energy?

Testing general relativity during the interplanetary cruise to Uranus requires accurate acceleration and gravity measurements.

(2) Solar wind and heliosphere:

- What is the structure and dynamics of the solar wind beyond 10 AU?
- How does the solar wind energy dissipation evolve with distance to the Sun? With the solar cycle?
- How does the solar wind interact with cosmic rays? With interplanetary dust? With the interstellar medium?

Sampling the solar wind and plasma/wave processes at work requires accurate magnetic field, radio, plasma and dust measurements together. Observations of energetic neutral atoms will remotely probe the termination shock.

(3) Small bodies:

- What is the origin, evolution and composition of centaurs such as Chiron?
- Are they active? Do they display a remanent magnetic field? How do they interact with the solar wind? Are they a source of interplanetary dust?

The characterization of one or several small bodies requires remote imaging at visible and infrared wavelengths and plasma/magnetic field measurements within the surrounding solar wind. Dust observations would also be strongly advantageous to understanding these bodies and the environment in which they reside.