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The comparative exploration of the ice giant planets with twin spacecraft: Unveiling the history of our Solar System

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ABSTRACT

In the course of the selection of the scientific themes for the second and third L-class missions of the Cosmic Vision 2015–2025 program of the European Space Agency, the exploration of the ice giant planets Uranus and Neptune was defined "a timely milestone, fully appropriate for an L class mission". Among the proposed scientific themes, we presented the scientific case of exploring both planets and their satellites in the framework of a single L-class mission and proposed a mission scenario that could allow to achieve this result. In this work we present an updated and more complete discussion of the scientific rationale and of the mission concept for a comparative exploration of the ice giant planets Uranus and Neptune and of their satellite systems with twin spacecraft. The first goal of comparatively studying these two similar yet extremely different systems is to shed new light on the ancient past of the Solar System and on the processes that shaped its formation and evolution. This, in turn, would reveal whether the Solar System and the very diverse extrasolar systems discovered so far all share a common origin or if different environments and mechanisms were responsible for their formation. A space mission to the ice giants would also open up the possibility to use Uranus and Neptune as templates in the study of one of the most abundant type of extrasolar planets in the galaxy. Finally, such a mission would allow a detailed study of the interplanetary and gravitational environments at a range of distances from the Sun poorly covered by direct exploration, improving the constraints on the fundamental theories of gravitation and on the behavior of the solar wind and the interplanetary magnetic field.

1. Introduction

The planets of our Solar System are divided into two main classes: the terrestrial planets, populating the inner Solar System, and the giant planets, which dominate the outer Solar System. The giant planets, in turn, can be divided into the gas giants Jupiter and Saturn, whose mass is mostly constituted of H and He, and the ice giants Uranus and Neptune, whose bulk composition is instead dominated by the combination of the astrophysical ices H_2O, NH_3 and CH_4 with metals and silicates. While H and He constitute more than 90% of the masses of the gas giants, they constitute no more than 15–20% of those of the ice giants (Lunine, 1993). The terrestrial planets and the gas giants have been extensively studied with ground-based observations and with a large numbers of dedicated space missions. The bulk of the data on the ice giants, on the contrary, has been supplied by the NASA mission Voyager 2, which performed a fly-by of Uranus in 1986 followed by one of Neptune in 1989.

The giant planets likely appeared extremely early in the history of the Solar System, forming across the short time-span when the Sun was still surrounded by a circumstellar disk of gas and dust and therefore predating the terrestrial planets. The role of the giant planets in shaping the formation and evolution of the young Solar System was already recognized in the pioneering works by

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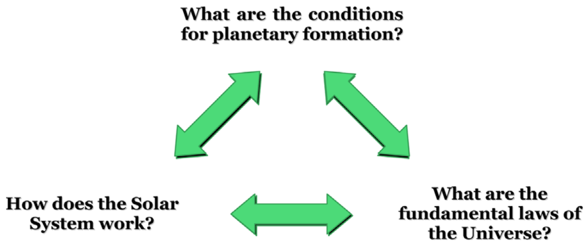

Fig. 1. Scientific themes of ESA Cosmic Vision 2015–2025 program addressed by a space mission to the ice giants Uranus and Neptune.

Oort and Safronov in 1950–1960. In particular, Safronov (1969) suggested that Jupiter's formation would have injected new material, in the form of planetesimals scattered by the gas giant, in the formation regions of Uranus and Neptune. More recently, a revised interpretation of planetary formation, obtained by studying extrasolar planetary systems, gave rise to the idea that the Solar System could have undergone a much more violent evolution than previously imagined (e.g. the Nice Model for the Late Heavy Bombardment, Tsiganis et al., 2005), in which the giant planets played a major role in shaping the current structure of the Solar System.

The scientific case of a space mission to both the ice giants Uranus and Neptune and to their satellite systems and the associated mission concept were first illustrated in the white paper "The ODINUS Mission Concept"[1] submitted to European Space Agency (ESA) in response to its call for white papers[2] for the definition of the scientific themes of the L2 and L3 missions. The purpose of this paper is to provide an updated and expanded discussion, building on the feedbacks the ODINUS white paper received from ESA and the scientific community at large, of this scientific case and of its relevance for advancing our understanding of the ancient past of the Solar System and, more generally, of how planetary systems form and evolve. While we will mainly focus on the open questions that the comparative exploration of the ice giants can address, to better illustrate the challenges presented by performing such a task within a single space mission and the feasibility of the proposed approach, we will also provide a concise but updated description of the ODINUS mission concept, based on the ideas discussed in the white paper and on the results of the following interactions with ESA and the scientific community.

From the perspective of ESA Cosmic Vision 2015–2025 program, the focus of such a mission and of this paper is on the first scientific theme "What are the conditions for planetary formation and the emergence of life?" (see Fig. 1). The study of the formation of the Solar System, however, cannot be separated from that of its present state and of the physical processes that govern its evolution. In discussing the scientific case for a mission to the ice giants, therefore, we will address also the second and third scientific themes 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?" (see Fig. 1). In the following we will use these scientific themes of the ESA Cosmic Vision 2015–2025 program as the guideline to discuss the scientific case for a mission to the ice giants and their satellite systems (Sections 2–4). The ODINUS mission concept and the scientific rationale of its twin spacecraft approach will be discussed in Section 5 together with the preliminary assessment of its feasibility performed by ESA. Finally, in Section 6 we will summarize the outcomes of the selection of the scientific themes for the L2 and L3 missions by ESA, with a focus on the evaluation of the scientific relevance and timeliness of the exploration of the ice giants and on future prospects.

2. Theme 1: what are the conditions for planetary formation and the emergence of life?

In this section we will briefly summarize how our understanding of the processes of planetary formation has evolved across the years, discuss their chronological sequence for what concerns the Solar System and highlight how the exploration of Uranus, Neptune and their satellite systems can provide deeper insight and better understanding of the history of the Solar System and how it compares to what we learned from the extrasolar systems discovered to date. It must be noted that the present knowledge on this subject is limited by current observational capabilities and likely supplies only an incomplete view. However, it is not easy to provide a sense of how our knowledge of exoplanets will evolve by the time an L class mission to the ice giants will be launched (currently, no earlier than L4 or 2040). Future space telescopes like ESA M3 Plato and NASA Transiting Exoplanet Survey Satellite (TESS) will explore regions of the phase-space currently unreachable, making it difficult to predict whether the new exoplanets will conform to the partial picture we can draw so far or if we are going to be surprised once more. Concerning the characterization of exoplanets, the James Webb Space Telescope (JWST) will surely provide information on the atmospheric composition of several extrasolar planets but dedicated missions, like ESA M3 mission candidate Exoplanet Characterization Observatory (EChO), for the systematic investigation of atmospheric composition are not currently planned. For further discussion on the subject we refer the readers to Turrini et al. (2014) and references therein.

2.1. The evolving view of planetary formation: Solar System and exoplanets

The original view of the set of events and mechanisms that characterize the process of planetary formation (Safronov, 1969) was derived from the observation of the Solar System as it is today. This brought about the idea that planetary formation was a local, orderly process that produced regular, well-spaced and, above all, stable planetary systems and orbital configurations. However, with the discovery of more and more planetary systems and of free floating planets (Sumi et al., 2011) through ground-based and space-based observations, it is becoming apparent that planetary formation can result in a wide range of outcomes, most of them not necessarily consistent with the picture derived from the observations of the Solar System. The orbital structure of the majority of the discovered planetary systems seems to be strongly affected by planetary migration due to the exchange of angular momentum with the circumstellar disks (see e.g. Papaloizou et al., 2007 and references therein) in which the forming planets are embedded, and by the so-called "Jumping Jupiters" mechanism (Weidenschilling and Marzari, 1996; Marzari and Weidenschilling, 2002), which invokes multiple planetary encounters, generally after the dispersal of the circumstellar disk, with chaotic exchange of angular momentum between the different planetary bodies involved and the possible ejection of one or more of them.

The growing body of evidence that dynamical and collisional processes, often chaotic and violent, can dramatically influence the evolution of young planetary systems gave rise to the idea that also our Solar System could have undergone the same kind of

[1] http://odinus.iaps.inaf.it or on ESA website, http://sci.esa.int/jump.cfm?oid=52030. The ODINUS acronym is derived from the main fields of investigation of the mission concept: Origins, Dynamics and Interiors of the Neptunian and Uranian Systems.

[2] See ESA's website at http://sci.esa.int/Call-WP-L2L3.