Planetary and Space Science 104 (2014) 108–121

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Neptune and Triton: Essential pieces of the Solar System puzzle

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ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form
1 May 2014
Accepted 12 May 2014
Available online 6 June 2014

Keywords:
Neptune
Triton
Solar System exploration

ABSTRACT

The planet Neptune and its largest moon Triton hold the keys to major advances across multiple fields of Solar System science. The ice giant Neptune played a unique and important role in the process of Solar System formation, has the most meteorologically active atmosphere in the Solar System (despite its great distance from the Sun), and may be the best Solar System analogue of the dominant class of exoplanets detected to date. Neptune's moon Triton is very likely a captured Kuiper Belt object, holding the answers to questions about the icy dwarf planets that formed in the outer Solar System. Triton is geologically active, has a tenuous nitrogen atmosphere, and is predicted to have a subsurface ocean. However, our exploration of the Neptune system remains limited to a single spacecraft flyby, made by *Voyager 2* in 1989. Here, we present the high-level science case for further exploration of this outermost planetary system, based on a white paper submitted to the European Space Agency (ESA) for the definition of the second and third large missions in the ESA Cosmic Vision Programme 2015–2025. We discuss all the major science themes that are relevant for further spacecraft exploration of the Neptune system, and identify key scientific questions in each area. We present an overview of the results of a European-led Neptune orbiter mission analysis. Such a mission has significant scope for international collaboration, and is essential to achieve our aim of understanding how the Solar System formed, and how it works today.

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http://dx.doi.org/10.1016/j.pss.2014.05.008
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1. Introduction

The primary aim of this paper is to review what we currently know about the Neptune planetary system, and to highlight the many fundamental scientific questions that remain unanswered. This review is based on a white paper that was submitted to the European Space Agency (ESA) in May 2013, to inform the selection of the science themes that will be addressed by the second and third large missions in the ESA Cosmic Vision Programme 2015–2025.

Neptune is classified as one of the giant planets, along with Jupiter, Saturn, and Uranus, and additionally forms a subgroup with Uranus called the “ice giants”, because both planets are primarily composed of “ices” (volatile elements heavier than hydrogen and helium). However, there are fundamental and important differences between the Uranus and Neptune planetary systems, which their common classification as ice giant planets should not obscure. The Neptune system is unique, providing opportunities for major advances across multiple scientific fields that cannot be made in any other planetary environment.

Neptune orbits the Sun at a distance ~30 times greater than the mean Sun–Earth distance (an Astronomical Unit, AU). A Neptune day is just over 16 h long, and a planetary obliquity of ~30° leads to seasons over Neptune's ~165-year orbit. The planet is surrounded by a system of rings and icy moons (6 regular, 7 irregular). Triton, by far the largest moon, very likely formed as a dwarf planet in the Kuiper belt (like Pluto) before being captured by Neptune. This makes Triton a unique planetary satellite in the Solar System.

Voyager 2 is the only spacecraft that has encountered Neptune to date, flying by the planet on 25 August 1989 when it was summer in Neptune's southern hemisphere (Stone and Miner, 1989). Fig. 1 shows *Voyager 2* imaging of Neptune during approach to the planet (Smith et al., 1989). The combination of this brief encounter and ground-based and space-based telescope observing campaigns have shown us that Neptune has the most meteorologically active atmosphere in the Solar System, despite its distance from the Sun, and that Triton has been (and could currently be) geologically active (see the review by Cruikshank (1995)). The Neptune system is barely explored compared to other planetary systems, and never with modern spacecraft instrumentation.

Sections 2 and 3 of this paper are dedicated to outlining the current state of knowledge, and defining key scientific questions, concerning the planet Neptune and its moon Triton, respectively. Each sub-section deals with one of the various science themes of Neptune/Triton science. We propose that the host of open questions put forward in Sections 2 and 3 make further spacecraft exploration of the Neptune system a priority for future Solar System exploration. Thus, in Section 4 we define further science questions that could potentially be addressed by a spacecraft bound for the outermost planet. Finally, in Section 5 we present an overview of a recent European-led Neptune orbiter mission analysis.

2. Neptune

2.1. Formation and implications for the Solar System and exoplanets

While there has been debate about Neptune's formation, a leading theory has now emerged (Gomes et al., 2005; Tsiganis et al., 2005; Morbidelli et al., 2005). It is postulated that Neptune formed at around 12–15 AU via planetesimal accumulation, before migrating to its present orbit at ~30 AU through a process of angular momentum exchange with a disk of planetesimals that initially extended out to 30–35 AU, interacting with the planets via gravitational scattering (Tsiganis et al., 2005). This scenario is supported by the higher density of solid material closer to the Sun (typical of protoplanetary disks) that would have lead to a shorter planetary accretion time, and explains the dynamical structure of the Kuiper Belt (~30–50 AU, remnants of the planetesimal disk), the possible occurrence of the cataclysmic late heavy bombardment on the terrestrial planets, and the observed compositional diversity of the asteroid belt.

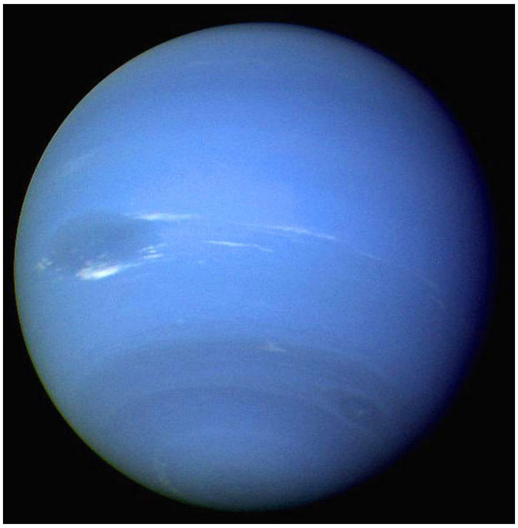

Fig. 1. Neptune, captured by the *Voyager 2* narrow-angle camera. Credit: NASA/JPL.

This leading theory highlights the importance of Neptune for Solar System formation and configuration, as illustrated in Fig. 2. Neptune effectively pushed the outer boundaries of our Solar System (Morbidelli, 2004). However, the process by which Neptune formed through accretion of planetesimals is poorly constrained. In addition, present understanding of the composition, configuration, and dynamics of the early Solar System is far from comprehensive, and our best models still cannot explain a number of features of the present day Solar System. Accurate knowledge of the physical properties of Neptune is of paramount importance for progress in all these areas. The size and mass of Neptune's core and its composition (rock/ice fraction) are crucial parameters for the improvement of planetary formation theories (Goldreich et al., 2004; Mordasini et al., 2011), and for revealing the composition of the solar nebula. Knowledge of the properties and composition of interplanetary dust at Neptune's orbit (particularly originating from comets) would also lead to significant progress in this field.

One of the mysteries concerning Neptune's formation stems from the fact that it had to form after Jupiter and Saturn, since it did not accrete as much gas as these two other giant planets. Its core likely reached completion in the later stages of solar nebula evolution, when the gas density was low due to viscous accretion and photoevaporation. How the growth and migration of Jupiter and Saturn delayed the accretion of Neptune's atmosphere is not completely clear (Jakubik et al., 2012). In this context, a detailed knowledge of the chemistry and composition of Neptune's atmosphere is essential for understanding how, where, and when the planet accreted it.

Impacts with large bodies in the early phases of their evolution have significantly affected the present state of the planets. While Uranus appears to have been radically altered by a potential giant impact (or even two) that not only tilted its spin axis (Safronov, 1966; Morbidelli et al., 2012) but also produced its low internal heat flux (Podolak and Helled, 2012), Neptune appears to have been affected by impacts in a different way. Its obliquity is comparable to that of the Earth and the interior is possibly more mixed with respect to that of Uranus, which would explain the