Science and Exploration in the Outer Solar System in 2050. A. A. Simon (NASA Goddard Space Flight Center)

Introduction: The best way to approach a vision 35 years into the future is to begin by looking back. A snapshot of the state of knowledge of the outer solar system in 1980 is quite different from what we know today. Voyager 1 and 2 had just flown by Jupiter in 1979 and were approaching Saturn for 1981 encounters, leaving the Uranus and Neptune systems still fully unexplored. Although the Jupiter encounters revealed Io as an active moon, and the planet's fast moving clouds were observed, our view of the solar system was still of bodies that were rather static and unchanging. Even our knowledge of solar system formation was one of planets that formed neatly in place.

We now know that the bodies in the outer system likely migrated vast distances during their formation, affecting the formation of the rest of the solar system. We have also witnessed multiple objects impacting Jupiter several times and observed geysers on Enceladus and Triton, weather and seasons on Titan, and many other dynamic phenomena. In other words, the paradigm has shifted to viewing planets as active and evolving. We now even search for possible signs of life under the surfaces of the moons outer solar system, a concept easily dismissible 35 years ago.

Current Goals: Based on current knowledge, the Planetary Science Decadal Survey (PSDS) identified overarching science themes and exploration goals for the 2013-2022 time frame, along with recommended missions to many bodies of the outer solar system, including Europa, Uranus, the Trojan asteroids, Enceladus and more. If we assume that these missions occur on schedule and meet their science goals, we further advance our knowledge in key cross-cutting areas.

The PSDS Giant Planets chapter focused on the exploration of the four giant planets and defined three overarching science themes: Giant Planets' Role in Promoting Habitable Environments, Giant Planets as Groundtruth for Exoplanets, and Giant Planets as Laboratories for Properties and Processes on Earth. These themes involve exploration of the planet atmospheres and magnetospheres, as well as the rings and satellite systems, with an eye toward understanding the solar system as a whole by studying the smaller, but pivotal, pieces.

Decadal Missions: The main Giant Planet mission recommendations were a New Frontiers Saturn Probe mission, as well as a strategic Uranus-system orbiter and probe mission. Other focused missions were also recommended for key outer planet satellites, such as Europa, Enceladus and Io. In particular, the probe missions both provide significant *in situ* characterization, completing our knowledge of the upper atmosphere of these two giant planets, as well as detailed remote sensing of the Uranus atmosphere, magnetosphere, rings, and satellite system.

These missions, when combined with results from Cassini for Saturn and Galileo and Juno for Jupiter, will further constrain our understanding of solar system formation and atmospheric processes, but undoubtedly will raise new questions. However, each of the Giant Planet systems is different, with varying size, solar distance, migration history, and seasonal influence. Thus, we need to understand each individually, as well as in a combined picture, to best address the crosscutting Decadal themes. Under the assumption that a Uranus mission will occur first, *a Neptune orbiter and probe mission is crucial for completing the characterization of the unique properties of the major bodies in the solar system and would be a high priority if it has not been initiated by 2050.*

Science Priorities in 2050: With existing data, and the proposed Decadal missions, many bulk properties will be constrained for 3 of the 4 giant planets. However, there are many areas that will still be unaddressed and are important for better understanding both exoplanets and atmospheric processes in comparison with Earth. For example:

1) *Seasonal effects*: the yearly variations of the outer planets are not well understood. Given the long orbital periods for Uranus (84 yrs.) and Neptune (165 yrs.), and even our limited coverage of the Jovian (12 yrs.) and Saturnian (30 yrs.) yearly cycles, there is much to be understood about the connections between solar insolation and convective activity, as well as other atmospheric wave-driven cycles. Even activity on the satellites may have seasonal components. Long-term remote sensing coverage is needed for each planet.
2) *Interior structure*: another key to understanding winds and weather, as well as observed atmospheric temperatures, is knowledge of the deep interior structure, equations of state, and the effects/likelihood of helium rain. New laboratory work, science instrumentation, and analysis techniques hold promise for beginning to remotely explore those regions.

And many more…

Summary: Given the expected state of knowledge for the Giant Planets at the end of the Decadal period, the highest science and exploration priorities can be projected for 2050. Our understanding of giant planet systems is critical to informing exoplanet, solar system formation, and atmospheric dynamic studies.