KBO Science with Argo – A Voyage through the Outer Solar System

J.A. Stansberry (U. Arizona), C. J. Hansen (JPL), A. S. Aljabri (JPL), D. Banfield (Cornell), E. B. Bierhaus (Lockheed Martin), M. Brown (CalTech), J. E. Colwell (U. Central Florida), M. Dougherty (Imperial College), A. R. Hendrix (JPL), K. Khurana (UCLA), D. Landau (JPL), A. McEwen (U. Arizona), D. A. Paige (UCLA), C. Paranicas (APL), C. M. Satter (JPL), B. Schmidt (UCLA), M. Showalter (SETI Inst.), T. Spilker (JPL), L. J. Spilker (JPL), N. Strange (JPL), M. Tiscareno (Cornell), W.M. Grundy (Lowell Obs.), N. Haghighipour (PSI), K.S. Noll (STScI), E. Schaller (U. Arizona), S. Sheppard (Carnegie Inst.)

Some co-authors have recused themselves due to Decadal Survey panel obligations

Primary author contact: Candice Hansen, 626-438-5640, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, *candice.j.hansen@jpl.nasa.gov*

This white paper describes Kuiper Belt Object science to be achieved by Argo (Neptune and Triton science are described in separate white papers, authored by Candice Hansen)

Argo is a conceptual New Frontiers 4 mission to explore a *scientifically-selected* Kuiper Belt Object. A flyby through the Neptune system (including a close Triton encounter) opens up a large swath of trans-Neptunian space from which to select KBO targets. We estimate that the target could be chosen from about 30 KBO with diameters > 200km (10 with diameters > 400 km), 15 cold-classical KBOs, and 7 (known) binary KBOs. *Argo*'s payload is optimized to provide a detailed first-look characterization of the geology, composition, impact and tectonic history, volatiles/atmosphere, and solar-wind interaction of the KBO target. This payload and the Neptune flyby also provides the opportunity to complete our reconnaissance of former KBO, Triton. The payload is also well suited to study Neptune and its system of rings and moons, and to measure in detail seasonal changes on the surface of Triton, and in both its, and Neptune's, atmospheres (*via* comparison with Voyager data). By carefully focusing scientific goals, optimizing the payload, and using high-heritage instrument and spacecraft systems, *Argo* can provide this paradigm-shifting level of science within the New Frontiers cost envelope.

I. Introduction

Our understanding of the history of our Solar System has been revolutionized, largely because of the discovery of Kuiper Belt Objects (KBOs; Jewitt et al. 1992). Well over a thousand KBOs have since been discovered (e.g. Barucci et al. 2008), and they exhibit remarkable diversity in their properties. Geometric albedos range from a few percent to nearly 100%, and appear to be correlated with diameter, as well as (possibly) visible color and perihelion distance (Stansberry et al. 2008); cold-classical KBOs appear to be red and have high albedo (Doressoundiram et al. 2008; Brucker et al, 2009). Visible colors span the range from slightly blue to the reddest objects in the Solar System (Pholus). Visible and near-IR spectra run the gamut from profoundly bland to exhibiting absorptions (or emission peaks) due to organics, water, nitrogen, methane and other hydrocarbon ices, and silicates (e.g. Barucci et al. 2008b). Perhaps the most remarkable character of KBOs is the abundance of binary and multiple systems: among the cold-classical KBOs, 30% or more are probably binaries (Noll et al. 2008).

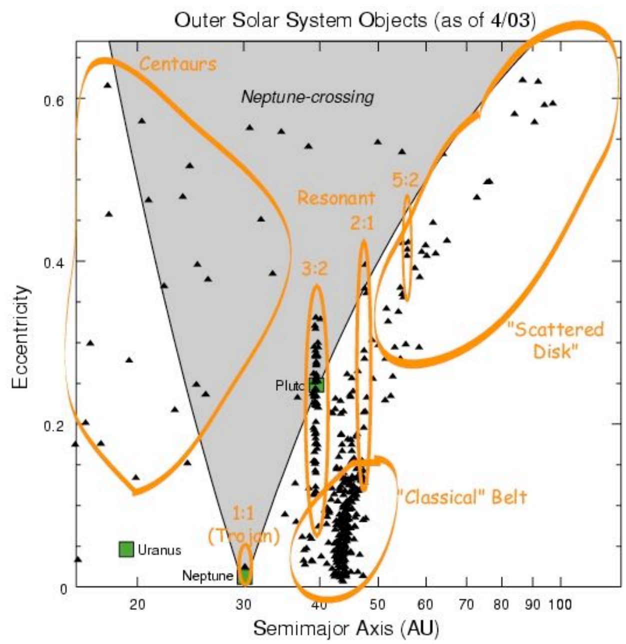

Figure 1. KBO's are classified as "classical", "resonant", "scattered" or "detached" by their orbital characteristics: eccentricity and semimajor axis. Most of Argos potential targets are classical KBOs, although some scattered and resonant objects are also possibilities. (Figure courtesy of the LSST Project (www.lsst.org/).)

The current number of KBOs, the dynamical structure of their orbits (Kavelaars et al. 2008) (Figure 1), and the diverse physical characteristics of the individual objects has spurred intense efforts at modeling the formation and evolution of the KBO population. These studies, started by Malhotra's (1993) explanation for Pluto's orbit, have resulted in a picture in which Saturn crossed through the 2:1 resonance with Jupiter, exciting the orbital eccentricities of Uranus and Neptune, which (as a result) interacted strongly with the primordial Kuiper Belt, suffering significant outward orbital migration. This scenario explains well the dynamical structure and present-day population of the Kuiper Belt, as well as the origins of the late heavy bombardment in the inner Solar System (Gomes et al. 2005, Morbidelli et al. 2005, Tsiganis et al. 2005, Levison et al. 2008). Given the dynamical richness of the Kuiper Belt, the possible links between its evolution and the evolution of the rest of the Solar system, the exceptional diversity of KBO physical properties, and the unprecedented number of binary KBO systems, it is frustrating that no missions after *New Horizons* are planned to explore the Kuiper Belt. Compounding that frustration is the fact that our next opportunity to visit Neptune and Triton will likely not occur until 50 years or more have passed since the Voyager encounter in 1989 (*Science Plan for NASA's Science Mission Directorate, 2007*).

Argo is an innovative mission concept for NASA's New Frontiers 4 program: it flies by Triton and Neptune, and continues on to explore a Kuiper Belt Object. Launch opportunities begin in

2015 and last through the end of 2019, with backup options in 2020. Voyager-like trajectories (i.e. with a Jupiter and/or Saturn gravity assist) are reasonably short (8-11 years to Neptune, and 3-5 additional years to a KBO), and offer Triton encounter speeds comparable to that of Voyager (<18 km/sec). We envision a mission that employs current spacecraft technology (similar to *New Horizons*) and a simple yet capable payload with flight heritage (see Table 2). By completing our reconnaissance of Triton (likely a captured KBO) and characterizing another KBO, ***Argo*** (along with *New Horizons*) will provide complementary insights into the complexity and diversity of objects in the Kuiper Belt, as well as significantly advancing our understanding of Neptune itself. The science return from ***Argo*** will be both more timely and of distinctly higher impact than possible KBO missions lacking a Neptune fly-by.

II. Scientifically-Selected Kuiper Belt Object

The Neptune encounter provides access to a huge cone of trans-Neptunian space (Figure 2): trajectory modeling shows that tens of *known* KBOs are accessible to ***Argo***, and the flyby geometry can be tailored to not only achieve science goals within the Neptune system, but continue on to a ***scientifically-selected Kuiper Belt Object*** afterward. For example, ***Argo*** could choose from ~5 KBOs with diameters greater than 400 km, ~30 KBOs larger than 200 km diameter, ~15 "cold-classical" KBOs (thought to be the most primitive, un-processed KBOs), and ~5 binary KBOs. The selection of the KBO target will be constrained by Triton science and flyby geometry and vice versa, so selection of the KBO and the Triton science objectives to be achieved will be an iterative process.

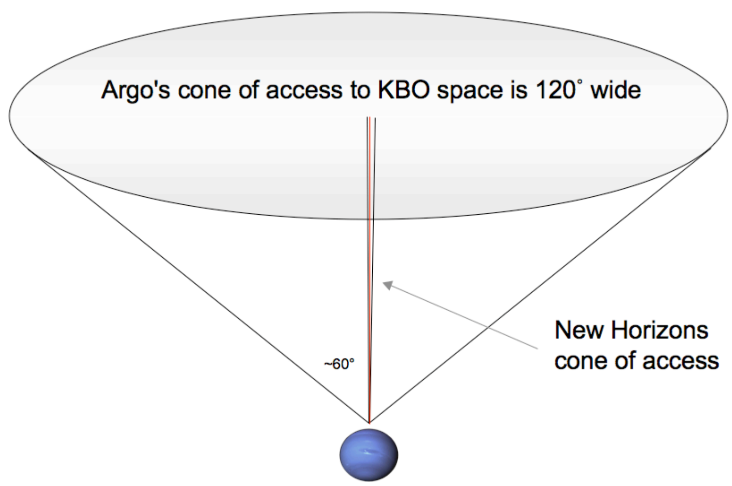

Figure 2. Argo's access to the Kuiper Belt compared with that of New Horizons. Neptune's mass provides a gravity assist that will permit selection of a KBO with the highest scientific interest. Detailed trajectory models have already identified 28 reachable KBOs brighter than $H_V = 7$ (diameters range from 200 – 700 km for an assumed albedo of 10%): 7 binaries (including (66652) Borasisi & (88611) Teharonhiawako), 19 classicals (mostly cold-classicals), 2 scattered objects (2005 RN_{43} being the largest of the 28 candidates), 2 resonant objects (2000 QL_{251}, a binary, and 2001 QF_{298}). More modeling will yield yet more candidates.

III. Kuiper Belt Object Science Objectives

This section focuses on KBO science objectives. In many areas, these are very similar to our Triton science objectives. Our overall objective is to guarantee that we obtain the necessary data for detailed comparison of Triton and the *Argo* KBO to one another, and to Pluto and the *New Horizons* KBO. Together, these observations will begin to provide significant insights into the diverse KBO population. In large part, the KBO and Triton science objectives drive the *Argo* science payload; the KBO objectives are summarized in Table 1. (Triton science objectives that are distinctly different are described in the *Argo* Triton white paper.)

Particulars of the KBO measurement objectives depend considerably on what target is chosen. Because target selection likely will not have been finalized before detailed instrument definition work must be completed, the instruments need to have broad capabilities appropriate for the exploration of primitive bodies in the outer Solar System. Luckily, Triton serves as an excellent proxy to a KBO target, and we do possess some detailed knowledge about a few of the larger KBOs (e.g. spectral features, albedos). Starting with that knowledge, we developed measurement objectives tailored for Triton and the largest KBOs, and then enhanced those to include conditions and objectives appropriate for a range of KBOs (e.g. lower albedo surfaces, more tenuous atmosphere).

Table 1. KBO Science Questions to be addressed by *Argo*.

Kuiper Belt Object Level 1 science objectives	Data Required	Instrument(s)
1. Determine the KBO's *bulk and system properties*	Measure shape and mass, look for satellites	High resolution camera, radio science link
2. Investigate interior structure: Is the KBO *differentiated*? Is there a *liquid ocean* inside the KBO? Is there a *remnant magnetic field* in the KBO?	Mass, Moment of inertia, existence of magnetic field	Radio science link, magnetometer
3. Characterize the *geology and surface composition;* establish *collisional history via cratering record*	Image surface and map surface volatiles and non-volatiles	High resolution camera, uv and near infrared spectrometers
4. Determine *photometric properties* of the surface	Images at range of phase angles; temperature map	High resolution camera, thermal mapper
5. Compare *volatile inventories compare between Pluto, Triton, and a KBO*	Map surface ice distribution	Near IR spectrometer
6. Does the KBO have an *atmosphere/ionosphere?* If so, how does it *interact with the solar wind?*	Radio, solar and/or stellar occultations; flux of escaping volatiles	UV spectrometer, mass spectrometer, radio science

Key KBO Science and Measurement Objectives

1. What can we learn about the *bulk and system properties*? Moderate resolution panchromatic global images constrain the KBO's size and overall shape. The shape is diagnostic of internal strength, and thereby constrains the composition and interior structure, and may also reflect on the collisional history of the target. The size, when combined with the mass (determined from radio science data), gives the bulk density. While we now have densities for a small sample of binary KBOs, Triton, and Pluto, we have no knowledge about the densities of moderate-sized solitary KBOs. The size, mass and density are critical for understanding the internal structure and composition, and the composition provides insight into physical and chemical conditions in the region of the proto-planetary nebula where the KBO formed. Deep, moderate-to-high-resolution images of the region surrounding the KBO could reveal the presence of rings and/or small satellites, either of which would be extremely important for understanding dynamical and collisional processes in the Kuiper Belt.

2. Is the KBO *differentiated*, and if so, what are the compositions of various internal layers? Is there a *liquid ocean* inside the KBO? Is there a *remnant magnetic field* in the KBO? *Argo* will measure the mass, and constrain the moment of inertia, of the KBO, providing direct Recent work by Hussmann et al. (2006) suggests that several of the largest KBOs may contain subsurface oceans. *Argo* will measure the induction response of the KBO to the changing interplanetary magnetic field (IMF) during close approach at an altitude of less than 0.5 body radius. Timing is not guaranteed, regardless, it will be critical to try and measure any signature of an internal magnetic field from the KBO: such a field would have profound implications for the interior structure and composition.

3. What can we learn about the *geology and surface composition*? What is the *cratering record*? Moderate-to-high-resolution color images of a significant fraction of the KBO surface enables many investigations, such as defining geologic units, and constraining cratering history and impactor size distribution. Crater morphology reveals aspects of the physical properties of the near-surface layers. The cratering record will provide key insight into the collisional history of the Kuiper Belt. Spatial variations in crater density can establish relative ages of surface units, and those age units can be related to variations in color, albedo or other surface characteristics. Tectonic and magmatic activity could be identified, and would provide insights into internal forces and heat sources, and potentially into their historical context. High-resolution images could reveal evidence of recent geomorphologic processes such as scarp retreat, mass wasting, or cryovolcanic activity.

Near-IR synoptic-scale spectral maps, with resolving power R ≈ 250, and far-IR temperature maps significantly enhance the geologic science return. Spectral maps provide specific compositional information. Correlating those with the higher spatial resolution color images may allow for the compositional information to be extended to smaller spatial scales, or may reveal that units identified based on visible-color maps contain various chemical species. Thermal imaging provides unique constraints on surface properties that are difficult to constrain from visible or near-IR spectral maps: conductivity, density and heat capacity.

4. How can *photometric properties* inform us about surface characteristics? Global and synoptic-scale color imaging at a range of phase angles constrain the phase-function of the surface (impossible to do from earth or earth orbit). The phase-function depends on the single-scattering albedo of particles very near, and on the micro-physical texture of, the surface. The phase function is also important for determining the bolometric albedo and energy balance.

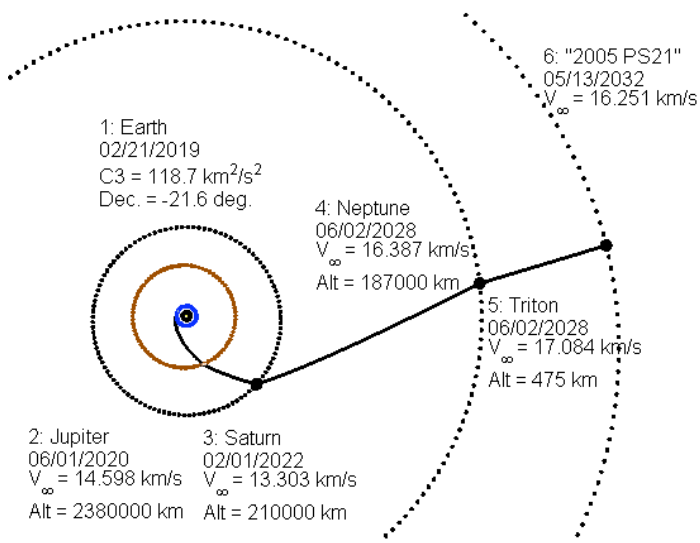

Fig. 3. This trajectory features a Jupiter and Saturn gravity assist that result in a flight time to Neptune of 9 years and a KBO flyby 4 years later.

5. Are *volatile ices present, in what quantity, and how are they distributed*? It is reasonable to expect that large KBOs may have volatile surface ices and tenuous atmospheres. Quaoar is an example that shows weak methane absorptions (Schaller et al. 2007; Dalle Ore et al. 2009), and is large enough that it is should be able to retain volatiles over the age of the Solar System (Schaller and Brown, 2007). Regardless of whether a very large KBO is selected as the target, a sensitive survey for volatile ices should be conducted, since they could indicate recent out-gassing or cryovolcanic activity activity. How are surface ices distributed? Seasonal volatile migration takes place on Triton and Pluto, which have nitrogen atmospheres in vapor pressure equilibrium with the surface frost (Hansen and Paige, 1996).

6. Does the KBO retain an *atmosphere,* and if so, how does it *interact with the solar wind?* Ultraviolet solar-occultation data will provide the most sensitive test for the presence of an atmosphere around the KBO, and could determine at least some of the likely chemical components. A radio occultation and high-phase imaging of the limb are important for characterizing density, temperature structure, and aerosols in the unlikely event that a denser atmosphere (≥1 μbar) exists. The radio occultation would also be highly sensitive to the presence of an ionosphere. An atmosphere might also reveal itself through an extended interaction signature detected by the particles and fields experiments.

III. Mission Description

Here we address just a few key aspects of the *Argo* mission concept. The most important question is "what are the opportunities to get to Neptune, and what are the characteristics of the trajectory options?" Flight system design must be achievable within the New Frontiers budget.

Trajectories

A window of opportunity to go to Neptune in a relatively short amount of time (8 – 11 years) using gravity assists at Jupiter and/or Saturn exists from 2015 to 2019, with a few backup launch opportunities in 2020. These trajectories are similar to the tour flown by Voyager, featuring a flyby of Jupiter ~1.5 years after launch, and Saturn flyby ~3 years after launch. The path from Saturn to Neptune is largely determined by the choice of the subsequent KBO. A balance of desired Triton viewing geometry and KBO selection determines details of the geometry of the Neptune flyby. Figure 3 shows an example of the type of trajectory and trip time that is available in 2019. Slower trajectories are also possible (skipping the gravity assists), and take about 15 years to reach Neptune. Such trajectories would probably result in higher costs, due to longer mission life, and would delay the ultimate science return by 5 to 10 years.

Table 2. Strawman Payload

Instrument	Heritage	Anticipated Capability
High-Resolution Visible Imager	NH LORRI	A high resolution camera will provide the highest-resolution images of Triton and a KBO, discrete features in Neptune's atmosphere, and high-phase-angle observations of the rings, over a wavelength range of 300 to 900 nm (the Voyager camera was only sensitive to ~ 600 nm).
Near-infrared Imager	NH Ralph	A near-IR instrument capable of mapping the distribution of surface frosts; this technology did not exist at the time of the Voyager Encounter. Distribution of CH_4, CO and CO_2 ices will address volatile transport on Triton and the KBO.
Ultraviolet Imaging Spectrograph	Reduced Cassini	The ultraviolet instrument will observe stellar and solar occultations to study Triton's, KBO's and Neptune's atmosphere and rings. FUV imaging will be used to map water distribution on the KBO and aurora on Neptune.
Thermal Imager	LRO Diviner	Multi-channel infrared filter radiometer, where each channel is defined by a linear, 21-element, thermopile detector array at the telescope focal plane, and its spectral response is defined by a focal plane bandpass filter.
Charged Particle Spectrometer	Messenger FIPS, Cassini CAPS	Measures the flux of ions as a function of mass per charge and the flux of ions and electrons as a function of energy per charge and angle of arrival relative to the instrument. Information on composition, density, flow velocity, and temperature of ions and electrons will be derived from the flux measurements. An energy range of a few eV to several tens of keV is desired for both ion and electron measurements.
Magnetometer	MGS	The magnetometer will look for signs of present or past dynamo magnetic field in Triton to try to infer the presence of a liquid ocean through electromagnetic induction studies that use the rotating magnetic field of Neptune as a sounding signal. A similar experiment will be performed at the KBO where the changing IMF field would be used as the primary inducing field.
Radio Science System	NH (hardwr) Cassini (architecture)	The RSS will measure bulk mass and low-order mass distribution of Neptune, Triton and the KBO; atmospheric pressure, temperature, density (if the KBO has an appreciable atmosphere), and ionospheric densities (ala Voyager at Triton).

Flight System

The *Argo* spacecraft would be functionally similar to the *New Horizons* spacecraft now *en route* to Pluto. Like *New Horizons*, *Argo* will need onboard data storage to retain the copious data taken during close encounters, for subsequent relay to Earth. Also like *New Horizons*, the *Argo* spacecraft would use a radioisotope power source (RPS) for electric power. An attractive option is to decouple high-gain antenna (HGA) pointing from science-instrument pointing by articulating the HGA via a gimbal, as is currently employed on Mars orbital missions. This affords significantly greater flexibility in scheduling science-data acquisition and downlink periods, with the possibility of doing them simultaneously. For a modest 10 W of RF power out, downlink data rates of 5 to 15 kbps are available depending on HGA diameter. By adhering to a *New Horizons* spacecraft level of complexity *Argo* will remain within the New Frontiers budget.

IV. Technology Needs

The Argo spacecraft would use a radioisotope power source for electric power. That power source could be an MMRTG (scheduled to fly on the MSL mission in 2009) or an Advanced Stirling Radioisotope Generator (ASRG) currently under development by NASA and DOE. ***The continued availability of radioisotope power source systems is an absolutely critical enabling technology**,* for *Argo* and all other missions to the outer Solar System.

V. Summary

Our understanding of the Kuiper Belt – particularly its key role in the early evolution of the Solar System – has revolutionized our understanding of the Solar System as a whole in recent years. Yet we know very little about the nature of Kuiper Belt Objects as a class. Voyager provided a tantalizing look at Triton, a large KBO that has undergone capture into orbit around Neptune. *New Horizons* will provide a more detailed look at another highly-evolved KBO, Pluto, beginning in 2015, and another, presumably smaller, more primitive, KBO some years later. *Argo* will provide a chance to visit a third *in situ* KBO, which can be selected from a list of tens of scientifically interesting objects including binaries, objects larger than 400 km, and cold-classical KBOs. With the addition of *Argo* data we will have explored just four of a vast and highly diverse population of KBOs.

The opportunities for exploration in the distant Solar System are by their very nature limited to *only* the New Frontiers and Flagship classes of mission. Furthermore, no spacecraft will have flown by either ice giant system in three decades, whereas *every other class of object in the Solar System* has had – or will have – at least a flyby by 2015, if not multiple flybys and/or orbiters. For all these reasons, *Argo* should be considered a top candidate for the New Frontiers 4 selection, to enable the continuing and timely exploration of our "home in space."

References

Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A. 2008. The Solar System Beyond Neptune: Overview and Perspectives. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, Arizona, pp. 3-10.

Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A. 2008b. Composition and Surface Properties of Transneptunian Objects and Centaurs. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, Arizona, pp. 143-160.

Brucker, M.J., W.M. Grundy, J.A. Stansberry, J.R. Spencer, S.S. Sheppard, E.I. Chiang, M.W. Buie 2009. High Albedos of Low Inclination Classical Kuiper Belt Objects. *Icarus* **201**, 284-294.

Dalle Ore, C.M. et al. 2009. Composition of KBO (50000) Quaoar. *A&A* **501**, 349.

Doressoundiram, A., H. Boehnhardt, S.C. Tegler, and C. Trujillo 2008.Color Properties and Trends of the Transneptunian Objects. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, Arizona, pp. 91-104.

Elliot, J. L., et al. 2000. The Prediction and Observation of the 1997 July 18 Stellar Occultation by Triton: More Evidence for Distortion and Increasing Pressure in Triton's Atmosphere. *Icarus* **148**, 347-369.

Elliot, J. L., et al. 2007. Changes in Pluto's Atmosphere: 1988-2006. *Astron. J.* **134**, 1-13.

Gomes, R., Levison, H. F., Tsiganis, K., Morbidelli, A.2005. Origin of the Cataclysmic Late Heavy Bombardment Period of the Terrestrial planets. *Nature* **435**, 466-469.

Hansen, C. J. and Paige, D. A. 1996. Seasonal nitrogen cycles on Pluto. *Icarus* **120**, 247-265.

Hussmann, H., Sohl, F., and Spohn T. 2006. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-Neptunian objects. *Icarus* **185**, 258-273.

Jewitt, D., Luu, J., Marsden, B. G. 1992. 1992 QB1. *IAU Circular* 5611.

Kavelaars, J., Jones, L., Gladman, B., Parker, J. W., Petit, J.-M. 2008. The Orbital and Spatial Distribution of the Kuiper Belt. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, pp. 59-69.

Levison, H. F., XXX 2008. Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune. *Icarus* **196**, 258-273.

Malhotra, R. 1993. The Origin of Pluto's Peculiar Orbit. *Nature* **365**, 819-821.

Morbidelli, A., Levison, H. F., Tsiganis, K., Gomes, R. 2005. Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature* **435**, 462-465.

Noll, K. S., W.M. Grundy, E.I. Chiang, J-L Margot, S. D. Kern 2008. Binaries in the Kuiper Belt. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, Arizona, pp. 345-363.

Schaller, E. and Brown, M. 2007. Volatile loss and retention on Kuiper Belt Objects. *BAAS* **39,** 511.

Schaller, E.L., and M.E. Brown 2007. Detection of Methane on Kuiper Belt Object (50000) Quaoar. *ApJL* **670**, L49-L51.

Stansberry, J.A., W. Grundy, M. Brown, D. Cruikshank, J. Spencer, D. Trilling, J-L. Margot 2008. Physical Properties of Kuiper Belt and Centaur Objects. In *The Solar System Beyond Neptune* (M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, A. Morbidelli, Eds.) The University of Arizona Press, Tucson, Arizona, pp. 161-179.

Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H. F. 2005. Origin of the orbital architecture of the giant planets of the Solar System. *Nature* **435**, 459-461.