SEARCHING FOR CONSTRAINTS ON THE CHRONOLOGY OF THE OUTER SOLAR SYSTEM FROM SATELLITE GEOPHYSICS.
T. V. Johnson[1], J. C. Castillo-Rogez[1], D. L. Matson[1], J. I. Lunine[1,2], (1) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109. (2) Lunar and Planetary Lab, 1629 E. University Blvd. Tucson, AZ 85721-0092.

Introduction: Recent astronomical observations suggest that the lifetime of gas and dust sufficient for making giant planets around Sun-like stars may be typically only two to five million years [1, 2]. Thus if short-lived radioactive isotopes (SLRI) with half-lives of 10 My were present in the circumstellar disk, they would be included in any planets formed. These isotopes would supply heat as they decayed. The challenge is to search for observations that test the validity of this scenario. In the Solar System, we believe that models of medium-sized satellites can be used for this purpose. Initial results suggest that they can also yield constraints on the time of formation and chronology of the outer Solar system. We address the reasons supporting this suggestion, status of our understanding of this problem, and the outstanding issues.

Context: The SLRI that are most significant for modeling the thermal evolution of Solar system objects are ^{26}Al and ^{60}Fe. Their origin (^{26}Al from Solar X-Wind, [3]; or both from supernova injection, [4]), their distribution in the early Solar system, and their initial concentrations are still matters of some debate. The recent discovery of calcium-aluminum inclusions in samples of the comet Wild 2 [5] (*Stardust* mission) is the latest major development. We use the CAI formation date as the reference time for our satellite models discussed below and the initial concentrations of ^{26}Al and ^{60}Fe have been defined for that time on the basis of meteorite studies.

Small satellites in the outer solar system (less than 1000 km in radius) provide the right conditions for the heat from SLRI to express itself in terms of observable geophysical properties. Temperatures of accreting materials are low (less than 100 K), and the small satellites gain a negligible amount of heat during accretion compared to the larger icy satellites. It is difficult to heat them with long lived radioactive isotopes (LLRI) since they lose heat too fast. That is, the time scale required for LLRI decay to heat the interior up to water ice creep temperature is much longer than the time scale for these objects to cool. Whether or not tidal dissipation is a significant heat source is a crucial issue.

The possible geophysical significance of SLRI was first mentioned by [6]. The modeling of icy satellites that included SLRI was suggested by several authors [e.g., 7]. However these studies used the amount of SLRI included in the models as a free parameter. Also, they did not develop the relationship between SLRI content and accretion date. The abundance of SLRI in the rock fraction is now better known, except for a large uncertainty in ^{60}Fe. The models must include this range. Otherwise, the main variable is the date of accretion. Within the uncertainties of the ^{60}Fe abundance, that date and the rock fraction fix the amount of radioactive isotopes in the model.

We have been searching for evidence that SLRI were available in the early, outer Solar system, using coupled thermophysical-dynamical modeling of the icy satellites. If SLRI are present, then the main parameters determining the satellites' evolution are the silicate mass fraction x_s and the time of formation. Significant SLRI heating lasts no longer than the first 10 My after accretion. Depending on x_s, SLRI decay heat will affect the evolution of porosity, thus lithospheric properties, or also result (for large x_s) in rapid, and complete, melting of the ice, drastically affecting the long-term evolution of the satellite.

First Results: We have suggested [8] that Iapetus formed between 2.5 and 5 My after CAIs production. Our objective was to explain Iapetus' non-hydrostatic shape and current spin rate. We showed that heat from SLRI decay results in early porosity decrease, necessary to maintain the 33-km non-hydrostatic difference between the equatorial and polar radii. The presence of ammonia could have played a similar role in decreasing porosity. However, ice thermal conductivity (even with ammonia present) is large and promotes rapid cooling before despinning could happen. We found that SLRI are needed to promote conditions suitable for tidal dissipation that triggered Iapetus' despinning and brought it to its present, synchronous, spin rate.

This study highlighted a series of uncertainties in the current understanding of icy satellites. First, the importance of convection in satellites, which are small, cold, and volumetrically heated for most of their history is currently work in development by Sotin *et al.* and Barr and McKinnon. Also, most large icy satellites undergo significant melting during accretion have already partially differentiated by the end of accretion. In small satellites, the internal temperatures progress slowly to the ammonia-water eutectic. The fate of this ammonia hydrate melt as a function of initial ammonia content has not been modeled. Neither has been its role in tidal dissipation. As mentioned above, the conditions in which tidal dissipation can become a significant heat source is a major modeling issue. No data are available for dissipation under the conditions of forcing frequency and temperature that apply to these satellites.

An alternative approach to the latter issue consisted of constraining Mimas' dynamical evolution from its current, anomalously large free eccentricity [9]. We found that the dissipation factor of Mimas' ice between 80 and 220 K (the maximum temperature achieved in Mimas for times of formation longer than 6 My after CAIs), is greater than $3x10^3$

There is a need for experimental data on the dissipative properties of planetary materials at tidal forcing frequencies. This is the reason why this work has served as a rationale for developing a new laboratory at the Jet Propulsion Laboratory to measure, among other properties, the dissipation factor of various ices, for temperature as low as 80 K [10].

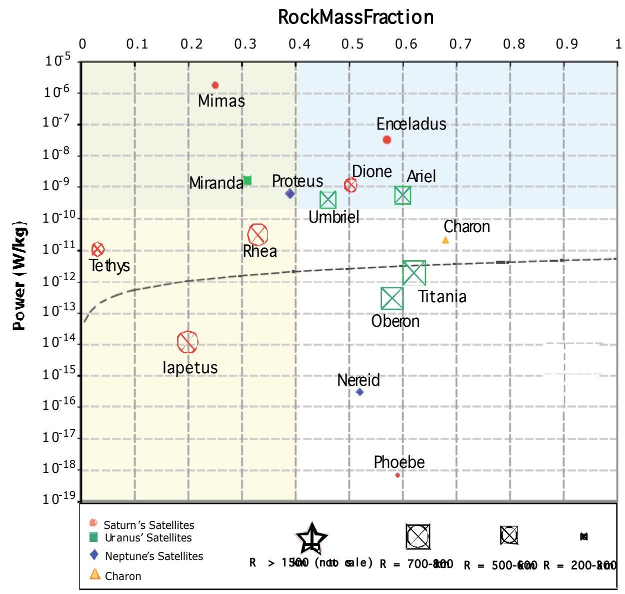
The Importance of Comparative Planetology: The concept that we can use the medium-sized Saturnian satellites to date the formation of the outer Solar system is viewed as "*an extraordinary claim that requires spectacular evidence*" (Steve Saunders, personal communication). We argue that the Mimas-Enceladus paradox is such evidence. It is the spectacular demonstration that tidal friction in a cold satellite is a marginal heat source. Both Mimas and Enceladus have the same, short, cooling time scale, and should follow a similar evolutionary path if they did not accrete SLRI. However, the warm temperatures reached in Enceladus' interior, necessary to explain the south pole geyser's content in molecular nitrogen and methane [11] cannot be explained by models that do not include SLRI. If we consider that Enceladus contains three times as much rock (in mass) as Mimas, then the solution to the paradox is obvious. SLRI heating results in early melting and differentiation of a rocky core in Enceladus [12].

More generally, comparative planetology and multidisciplinary studies are keys to progress in this research. Comparative planetology of satellites at the scale of the Saturnian system and between the Uranian and the Saturnian satellites is crucial because these objects cover a large range of densities and sizes (Figure 1). It is then possible to compare pairs of objects (e.g., Mimas and Enceladus, Rhea and Iapetus, Enceladus and Ariel, etc.) A multidisciplinary approach is also necessary to integrate available observational constraints in models. It might not be possible to find evidence of SLRI inclusion during accretion for all the satellites, considered individually, because in some cases there is little remaining evidence about their early history. Crater distribution, internal structure, current shape, hydrostatic equilibrium, geological activity can be symptomatic of early conditions. Extreme end-members, *e.g.*, rock-rich satellites, require special attention.

A rapid survey (Figure 1) indicates that several satellites share with Enceladus a relatively high x_s and dynamical properties favorable to significant tidal heat production over the long term. This is the case for example of Ariel. Could both Ariel and Enceladus have undergone a similar early history involving hydrothermal activity? Could Ariel currently exhibit intense geological activity? Can the difference in formation times of the Uranian and Saturnian satellites be assessed by studying these satellites?

In the same vein, could the fact that Callisto might be partially differentiated (i.e., late times, [13]), provide a further clue regarding the chronology of the outer solar system?

Figure 1. *Distribution of outer planet medium-sized satellites as a function of their rock mass fractions and the theoretical amount of tidal heating per kilogram of ice.*



Summary: We propose a new research direction whose implications are many. First, evidence that ^{26}Al was present in the early history of the outer Solar system, would constrain the origin of this isotope, and as such the origin of the Solar system itself. This research would also open the door to coordinating the different chronological scales used by the different fields in planetary sciences: cosmochemical, dynamical, geochronology, crater counting, and now satellite geophysics. As such, it is crucial that efforts be undertaken to search for further evidence of the effects of SLRI on outer Solar system objects, or for alternative approaches to successfully model observations at these satellites.

References: [1] Najita and Williams (2005) *ApJ* 635, 625. [2] Calvet et al. (2005) *ApJ* 630, 185. [3] Shu et al. (1993) *Science* 271, 1545. [4] Vanhala and Boss (2005) *ApJ* 575, 1144. [5] McKeegan (2006) *Science* 314, 1724. [6] Urey (1955) *PNAS* 41, 127. [7] Prialnik and Bar-Nun (1991) *ApJ* 355, 281. [8] Castillo et al. (2007a) *Icarus* in press. [9] Castillo *et al.* (2007b) in preparation. [10] Hays *et al.* (2007) LPS 38. [11] Matson *et al.* (2007) *Icarus* 187, 569. [12] Matson *et al.* (2007), LPS 38. [13] McKinnon (2006) *LPS* 37, 2444.

Acknowledgements: This work was carried out at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA.