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Searching for Constraints on the Chronology of the Outer Solar System From Satellite Geophysics

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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. 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 will address the reasons supporting this suggestion, status of our understanding of this problem, and the outstanding issues.

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. Their temperatures at accretion are low (less than 100 K), and they 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 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. 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. The SLRI that are most significant for modeling the thermal evolution of Solar system objects are 26Al and 60Fe. We use the CAI formation date as the reference time for our satellite models discussed below and the initial concentrations of 26Al and 60Fe have been defined for that time.

If SLRI are present, then the main parameter determining the satellites' evolution is the silicate mass fraction xs and the time of formation with respect to CAIs. The abundance of SLRI in the rock fraction is now better known, except for a large uncertainty in 60Fe. The models must also include this range. Significant SLRI heating lasts no longer than the first 10 My after accretion. Depending on xs, SLRI decay heat will affect the evolution of porosity, thus lithospheric properties, or also result (for large xs) in rapid, and complete, melting of the ice, drastically affecting the long-term evolution of the satellite. We will illustrate these effects by presenting the results we got for Iapetus, Enceladus, and Mimas in order to explain their characteristics: shape and spin period for Iapetus, presence of a core and hydrothermal geochemistry for Enceladus, and present eccentricity for Mimas. We will also demonstrate how forming Enceladus and Mimas in a few My after CAIs can explain the paradoxal difference in activity between these satellites. We will also report uncertainties in the current understanding of icy satellites highlighted by these models. First, the importance of convection in satellites, which are small, cold, and volumetrically heated for most of their history is currently work in development. 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. 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.

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. 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 or rock-poor satellites, require special attention.

Summary: We propose a new research direction whose implications are many. First, evidence that 26Al 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.

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