A NEW UNDERSTANDING OF THE INTERNAL EVOLUTION OF SATURNIAN ICY SATELLITES FROM CASSINI OBSERVATIONS

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Introduction: After less than two years in the Saturnian system, the Cassini spacecraft has provided us with a wealth of data likely to revolutionize our understanding of medium-sized icy satellites. We address some aspects of the geophysical concepts arising from the new observations, with respect to our state of knowledge since Voyager. In particular, we focus on dynamical evolution and geodynamical effects and their associated geological expressions.

New Geophysical Data: The Saturnian satellites masses are now determined within less than 0.5% uncertainty [1]. While the shape is not yet fully determined, the uncertainties in the densities are less than 5%, acceptable accuracy for most geophysical modeling. Rock mass fraction ranges between 3% in Tethys to 57% in Enceladus. The main change with respect to Voyager data is for Enceladus' whose density icreased by 60%. The very low density of Tethys, has been confirmed to be ~960 kg/m^3, which is anomalous and barely consistent with the shape data [2].

Constraints on the Origin: These satellite densities have been used as constraints on the origin of the Saturnian satellites. The weighted averaged density for the regular, medium-sized, Saturnian satellites is ~1220 kg/m^3. Johnson and Lunine (2005) [3] infer from this value that there was an enrichment in volatiles in the Saturnian subnebula with respect to the average composition of the Solar system. This is a potential constraint on the form of carbon in the Saturnian system. Another classic issue is how the satellite densities vary as a function of the distance from Saturn. The observed trend at Saturn does not follow a pattern similar to that for the Jovian satellites. This has implications for the origin and evolution of the satellite systems [4].

Thermal Modeling: Over the last twenty years, there has been a significant improvement in laboratory measurements of the properties of ice. For satellite thermal evolution models driven by the decay of long-lived radionuclides (labeled hereafter as LLRS), temperatures do not get above ~230K. After cooling of the Saturnian subnebula, the satellite surface temperatures are very cold (~75K). For these small bodies this leads to a rapid thickening of the lithosphere due to cooling from above. Warming of the interiors by LLRS operates on a longer time scales and builds up enough heat to potentially trigger geological activity between ~500-800 My after formation in the larger satellites. At that time, their lithospheres have thickened by several hundred kilometers. This implies that the smallest, low-density satellites, such as Mimas or Enceladus, are expected to undergo rapid freezing.

A major branch point in this scheme, however, is governed by the conditions under which convection starts. Here convection is driven by the high viscosity contrast between the surface and the interior. In the smaller satellites their low gravity can have a major influence on the significance of these differences. For example in Rhea, it takes ~800 My for internal temperatures to reach ~250 K, the temperature at which convection can "start". Next, however, is the transient phase necessary to effect convection. It can take up to 4 By to settle in toward the transitory state. A major consequence is that the Saturnian satellite surfaces can be very old and under the right conditions can record the history of dynamical evolution (orbital and spin rate). The sub-surface evolution would have been mainly affected by the evolution of surface temperatures, with the early phases dependent on Saturn's luminosity.

Now we consider the conditions for powering geological activity and dynamical evolution. Geological activity is especially important at Enceladus. A geyser associated with a thermal anomaly estimated to 4-8 GW, and a corresponding temperature of 140-180K [5]. This is significantly anomalous with respect to the expected average surface temperature of 75K for this South Polar area. Tidal dissipation is the most likely source of this anomaly [6, 7]. However as described by Castillo *et al.* [8] conditions are not favorable to the development of tidal dissipation in the smaller Saturnian satellites (because they are too cold, but also in Rhea and Iapetus, because their dynamical properties are not favorable) Tidal dissipation must be triggered by a significant thermal event in the histories of the satellites. Otherwise, little dynamical evolution and no visible geological activity are expected to take place. This problem has been studied in details by Castillo *et al.* [9] in the case of Iapetus' spin rate evolution. These authors have proposed that including short-lived radiogenic species (SLRS) in the early history of the satellite can provide the heat necessary to make the interior of the satellite more dissipative.

Now, we consider the implications of including SLRS throughout the whole Saturnian system. Short-lived radiogenic species provide intense heating for a period less than 20 My. They can set a body on an evolution that is completely different from models including only LLRS as the main, radioactive, heat source (accretionary heat does not factor in at all in this comparison). It is common knowledge that you "can melt anything with SLRS". SLRS can raise internal temperatures to ice melting point. They can raise temperatures high enough for tidal dissipation to start.

So, how do you know how much radioactivity to use? The answer came from our study of Iapetus. We found that only a very narrow range of ages were compatible with producing Iapetus' shape and delivering it to the synchronous spin rate. To specify SLRS content we assume that all the satellites were created at the same time as Iapetus. That assumption immediately fixes all the concentrations of all of the radioactive species. With this done, we can then follow the evolution of models for the various satellites.

Potential observations bear upon:

- Ongoing and Past Geologic Activity: Enceladus [10], kept its core warm for much longer than expected
- Surface Age: Crater Counting and resurfacing; the age at which the surface started retaining craters
- Shape equilibrium for a longer time
- Internal structure: (*e.g.*, Rhea) for which gravity field determination
- Dynamical evolution: Iapetus [9], Mimas [8], and other examples discussed during the meeting
- Surface composition (especially in craters, *e.g.*, Enceladus, Hyperion)

In Enceladus the temperature gets high enough for silicate hydration to occur. This produces volume changes, which, in turn, can influence internal and external evolution [10].

Whether conditions are intense enough that endogenic activity can start and be sustained until present is function of several different factors, depending on the differences in size and rock mass fraction between the satellites and their orbital evolution (especially eccentricity damping). For the satellites with the smallest density, *i.e.*, Mimas, Tethys, Iapetus, the situation is such that no geological activity should have theoretically taken place. Observations of activity at Tethys and Dione indicates that it has. Further coupled orbital-thermal-geological (including shape as a large-scale topography) evolution models will be presented for the other satellites.

We also examine the consequences of the presence of SLRS on Titan's early history. This yields entirely new models, much different from previously developed models. Now, differentiation occurs very early in the history and there is no subsequent core overturn. A high-level of hydrothermal activity can start, while such possibilities are less obvious in the coldest models [10].

Conclusion: Different lines of evidence, from geology and dynamical evolution, support the presence of short-lived radiogenic species in the early history of the Saturnian satellites. The approach was to take Iapetus' age as a reference. It then becomes possible to understand other features. Because they are expected to have very cold interiors, Saturnian satellites offer ideal conditions for detecting SLRS.

There has been an age determination for Iapetus and future studies will focus on repeating the approach to other satellites in order to see how formation times overlap. More generally, the presence of an intense episode heating in the early history of the icy satellites opens the door to new possibilities, for example high temperature geochemistry [10].

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

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