ENCELADUS' INTERIOR AND GEYSERS – POSSIBILITY FOR HYDROTHERMAL GEOCHEMISTRY AND N_2 PRODUCTION.

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Introduction: The Cassini observation of geysering associated with a thermal anomaly of 4-8 GW [1, 2], makes of Enceladus the "hottest" icy satellite in the outer Solar System. Astronomical observations indicate that the geyser might have had very large eruptions in the past, suggesting that we are presently observing a relative quiescent period [3].

Most probably, tidal dissipation is the main source of power for the South Pole thermal anomaly. However, it appears to be very difficult, if not impossible, for significant tidal dissipation to develop in a model of Enceladus that has long-lived radioactive isotopes as the only radiogenic species [4, 5]. Models presented so far show that it is difficult, if not impossible, to produce the observed power [5] if dissipation occurs only in the ice.

Further indication that high temperatures are reached in the interior is the presence of N_2 among the geyser products. N_2 in this form can only be produced by high-temperature dissociation of NH_3, discussed below. This makes Enceladus the second Saturnian satellite (after Titan) where molecular nitrogen is observed. Measurements by Huygens' GCMS [6] of noble gases in Titan's atmosphere indicate that Titan's atmospheric N_2 is not primordial but rather is the result of NH_3 processing. . If Enceladus' N_2 is primordial [7] it would imply that Enceladus and Titan had different initial compositions. We do not think that this is likely and we treat both objects as having similar initial compositions. As described below, the presence of N_2 in Enceladus could be the result of dissociation of NH_3 at high temperatures. Matson *et al.* (2005) [4] have produced such a model in which high interior temperatures (>1000K) are reached, offering the conditions for hydrothermal activity and associated geochemistry.

Approach and Model: We modeled the thermal evolution of Enceladus based on the recent suggestion that short-lived radiogenic species (SLRS) were present in the early history of Iapetus [9]. From that study Castillo *et al.* [9] derived the amount of short-lived radiogenic species (^{26}Al and ^{60}Fe) to be included in models for the different satellites, assuming that all of the satellites formed during the same period. This produces a temperature peak of up to 800K in the early history (< 10 My after formation) of Enceladus. Interior heat transfer is first governed by conduction. SLRS result in a rapid melting of the ice. Conditions are suitable for silicate hydration, which results in further temperature increases. This is accompanied by differentiation of the core. The core temperature keeps increasing and it reaches ~1300 K at about 100 My after formation.

Keeping the Core Warm: For internal temperatures this high in the core, magma reservoirs will be produced. Significant tidal dissipation will occur in the magma as a result of the interaction between its different components. The magma rheology is for a mixture of liquid, crystals and bubbles [10, 11]. Conditions are suitable for the magma viscosity to be about 10^{13}-10^{14}, at which maximum dissipation is reached for Enceladus' orbital frequency. The dissipation factor in the core for tidal frequencies is Q~1-10, and this can provide up to 100 GW, compared to 0.5 GW provided by the decay of long-lived radionuclides. Our calculations also indicate that some dissipation takes place in the low-viscosity ice present above the core and contributes to the total observed power.

Details of the size and evolution of the magma chamber need to be refined. We will present results for tidal dissipation with radial, latitude, and longitude dissipation factors. In this model of the satellite interior configuration there can be hydrothermal circulation at the interface between the core and the ice.

Additional modeling constraints can be provided by Enceladus' shape. Indeed, its shape corresponds to that of a satellite with an undifferentiated interior [2]. On the other hand, the presence of the warm region and our thermal model indicate that a differentiated interior is required. Thus, we might be observing relaxation at the South Pole and preservation of non-hydrostatic anomalies for the rest of the satellite.

Input for Geyser Mechanism: Measurements of the content of Enceladus' geysered gases have detected the presence of N_2 and CH_4 at concentrations of ~4% and 1.6% with respect to water [7]. Nitrogen has also been detected by the Cassini Plasma Spectrometer (CAPS) [12].

Conditions at the interface of Enceladus' core and hydrosphere are suitable for geochemical processes similar as the ones taking place in Earth's hydrothermal systems, *i.e.*, involving

$$2\ NH_3 \rightarrow N_2 + H_2$$ [*e.g.*, 13].

It is interesting to note that the amount of N_2 detected in the geyser (~4% [7]) corresponds to the solubility of N_2 in water for a temperature of $25^{o}C$ and a pressure of 1 bar (~1 km depth). This is a further constraint on the mechanism responsible for the geyser.

Further Implications: Enceladus is the only Saturnian satellite beside Titan where we have evidence for N_2 and CH_4 of endogenic origin. Both satellites also share relatively high uncompressed densities that are conducive to early differentiation and hydrothermal environments. We argue that high-temperature dissociation of NH_3 could have been responsible for the formation of Titan's atmosphere. Preliminary calculation indicates that all of Titan's initial NH_3 can be processed within a few My after formation. The mechanism by which the N_2 is stored and subsequently released remains to be elucidated.

Conclusion: We present a model for Enceladus' thermal evolution favorable to the production of high temperatures that are sustained until the present time. Models in which tidal dissipation takes place only in the ice layer provide insufficient heat to sustain observed thermal emission. Neither can they produce interior temperatures necessary to generate the N_2 observed in the South Polar Geyser.

The results from our Enceladus model are further evidence (along with results from models of the evolution of Iapetus [9] and Mimas [5]) that short-lived radionuclide species were present and active in the Saturnian system and played a major role in the subsequent evolution of Saturn's satellites, the consequences of which we are now observing. Also, determining how nitrogen and carbon were incorporated in the Saturnian satellites has many implications for the models of formation of the Saturnian subnebula.

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