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Sodium chloride as a clue to Enceladus' ocean mystery

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Abstract

Recent observations suggest that Saturn's satellite Enceladus may harbor a subsurface ocean containing dissolved salts. Here, we show that the NaCl content of an ocean can be used as an indicator of ocean structure. Because of the high solubility of NaCl salt, the NaCl concentration of an ocean should respond proportionally to addition and removal of liquid water. In other words, big oceans should be dilute, and small ones should be salty. We also explore some implications of a prominent outgassing model for Enceladus, and discuss some outstanding issues.

1. Introduction

Since the discovery of contemporary geological activity on Enceladus in 2005, there has been considerable debate concerning the existence of an aqueous ocean inside Enceladus [2-4]. The recent detection of salts, such as NaCl, in Saturn's E-ring [4] has perhaps swung the pendulum towards the pro-ocean side of the debate, although the issue is far from settled, as questions remain about source reservoirs and outgassing mechanisms of salts and gases [2-5]. These are hard problems, especially in light of limited observations, but one way we can begin chipping away at them is by constructing general models of the geochemistry of Enceladus' interior, which can provide frameworks for interpreting existing and future spacecraft data. Here, we construct a mass balance model for NaCl, and show that NaCl may be a useful probe of the structure of a subsurface ocean on Enceladus [1].

2. Approach

Several assumptions must be made to formulate a well-defined model of the geochemistry of NaCl on Enceladus. For example, we adopt the conventional viewpoint that Enceladus is a completely differentiated body, with a rock core, an ice shell, and an ocean possibly sandwiched between the two. We also assume that the rock core of Enceladus has a grain density and had a primordial chlorine abundance that is/was similar to those of CI chondrites [1]. By making these assumptions and a few others, the concentration of NaCl in an ocean can be estimated as a function of the mass fraction of the ice+ocean layer that is present as ocean, which is termed α [1]. The underlying concept is that dilution effects would control the NaCl content of an ocean.

The dimensions of Enceladus' ocean can also be related to parameter α by calculating the volume of oceans with different geometries [1]. Two variables are considered here: thickness of ice above ocean (z), and latitude of northernmost extent (LNE) of ocean (origin = south pole). We map out z-LNE-α space to determine which structures are compatible with certain values of α. In principle, the ocean's structure can be estimated as follows: (1) constrain the concentration of oceanic NaCl from observations and simulations; (2) constrain α from the concentration constraint; and (3) constrain z and LNE from the constraint on α. This will be illustrated below.

3. Results

Figure 1 shows the concentration of NaCl in an Enceladan ocean as a function of α from our nominal mass balance model. It can be seen that Enceladus should have a relatively dilute ocean unless a large fraction of its H_2O is locked up as ice. This is a consequence of the relatively high water/rock ratio of Enceladus, as indicated by its bulk density [3]. Enceladus thus offers a clear contrast to Earth, which has a salty ocean (Fig. 1) due to its richness in rock.

The relative masses of ocean and ice (i.e., α) could be estimated if the NaCl concentration of Enceladus' ocean were known. Unfortunately, there is insufficient evidence at present to presume that we know that number [5]. On the other hand, a detailed study of one outgassing scenario found that mass spectra of Na-rich E ring particles are reproduced well by laser dispersion of 0.05-0.2 molal NaCl [4]. This range thus provides a starting point for analysis of that particular scenario. Our geochemical model indicates that this range would correspond to α between 0.17-0.70 (Fig. 1). It follows that a sizeable portion of the H_2O on Enceladus may be liquid.

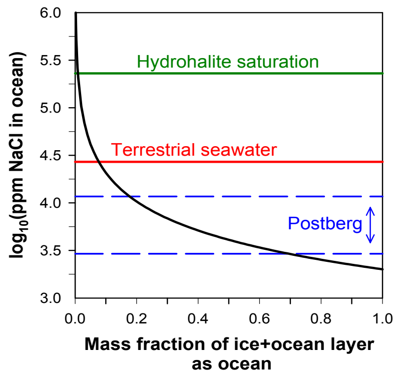

Figure 1: Predicted concentration of NaCl in an ocean on Enceladus (black curve) from the nominal model of [1]. The domain labelled "Postberg" represents a range in concentration that would be consistent with the outgassing scenario of [4].

The next step in our analysis is to relate the constrained range in α to potential structures (Fig. 2). There are many combinations of z and LNE that are compatible with α = 0.17-0.70. More interestingly, we also find that some values are always inconsistent with the above range in α. A notable example is that an ocean with α > 0.17 cannot be confined to latitudes more southerly than ~40°S (Fig. 2). A highly localized south polar sea would be too salty. Thus, present data suggest that Enceladus may have an ocean underlying terrains significantly northward of the geologically active south polar region (55°S).

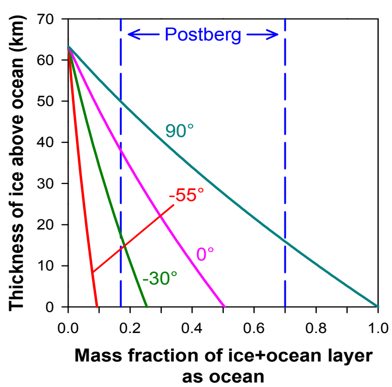

Figure 2: Relationships between thickness of ice above ocean and mass fraction of the ice+ocean layer that is present as ocean, with contours of latitude of northernmost extent of ocean. The "Postberg" domain here derives from that in Fig. 1. Northern latitudes are positive, and southern are negative.

6. Discussion

The values derived above should provide a useful starting point for future oceanographic studies of a possible Enceladan ocean. However, they may constitute only a subset of what is possible. As pointed out by [5], other models might be able to explain present data as well or better than [4]. It is thus important to keep an open mind. Our ability to interpret NaCl on Enceladus can be improved greatly by addressing the following questions: (1) Did the salts detected in space come from an ocean? (2) If so, can we determine their aqueous concentrations? These are not easy questions, and may take decades to answer. Salt-bearing ice or meltwater within Enceladus' ice shell could contribute to Enceladus' plumes [5]. Outgassing processes, such as mixing or condensation, may modify the salt content of ice grains [4]. Therefore, specifics may change as we learn more, but the general pictures developed here should still provide a solid theoretical foundation.

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