Enceladus' Interior: A Liquid Circulation Model. D. L. Matson[1], T. V. Johnson[1], J. I. Lunine[2], J. C. Castillo-Rogez[1], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109, USA (dmatson@jpl.nasa.gov), [2]Dipartimento di Fisica, Università degli Studi di Roma "Tor Vergata", 00133 Rome, Italy.

We investigate a model for Enceladus' interior in which the requirements of supplying water, gas and dust, to the eruptive plumes and matching the observed heat flow are accomplished by a relatively deeply circulating brine solution.

Data on Enceladus' eruptive plumes have suggested that the material seen in eruption was necessarily in contact with liquid water. On the basis of the presence of ammonia in the plume gas Waite et al. [1] suggested that the jets may originate from a liquid water region under Enceladus' icy surface. A similar suggestion was also made on the basis of observations of the dust particles entrained with or ejected by the eruptive plumes: Postberg et al. [2] noted that the presence of "…grains that are rich in sodium salts (0.5–2% by mass) … can arise only if the plumes originate from liquid water." Toward this end they developed a detailed model for the physics of the eruptions. We adopt their model for producing the eruptive plumes.

Furthermore, Waite et al. [1] regard the presence of some of the chemical species in the plumes as evidence for interactions with an ice layer presumably overlying the liquid water reservoir. They suggest that this could be in the form of dissociation of clathrate hydrates [3]. They conclude "…that the plume derives from both a liquid reservoir as well as from degassing, volatile-charged ice."

In addition to the chemical constraints just discussed, there is a relatively large amount of heat flowing out of Enceladus' south polar region. The total heat emission is ~15 GW [4, 5].

We consider a model in which the heat and chemical species are brought up to the surface from a reservoir or "ocean" located below the ice crust. This ice crust may be many tens of kilometers thick. This "deep" source is to be distinguished from relatively small reservoirs that may exist close to the surface and are closely related to the eruption mechanism and the coupling of heat to the surfaces from which it is radiated to space. Transit of water to the surface is via vertical conduits. The Cassini INMS data suggest that the water has a relatively large gas content of order a few percent. As "ocean" water travels upward, dissolved gases exolve, forming small bubbles as the pressure is released. The density of the bubbly liquid is less than the density of the ice and it is able to move upward. This part of the model is a variant of the "Perrier Ocean" model that Crawford and Stevenson [6] considered for Europa. A related model was studied for Ganymede by Murchie and Head [7].

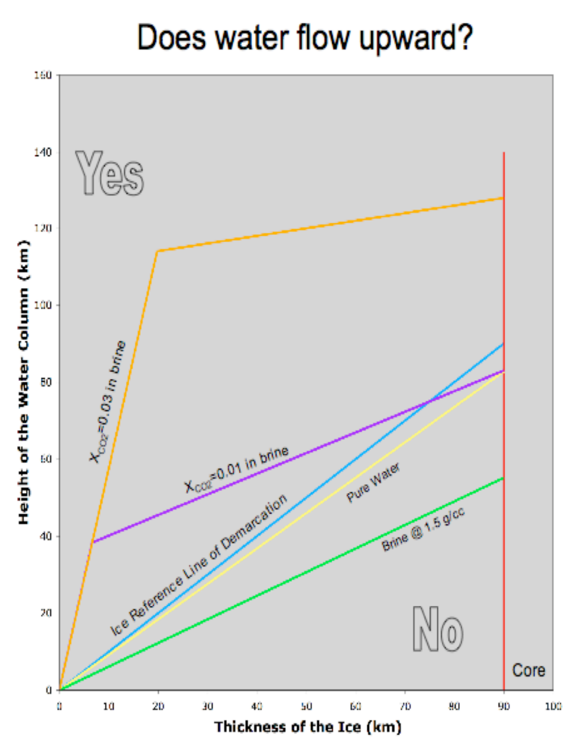

Fig. 1. Buoyancy considerations. Abscissa is the thickness of the ice layer. The ordinate is the equilibrium height that a liquid column can reach in a vertical conduit connecting the reservoir just below the ice with the surface. The Ice reference line shows the demarcation between solutions that can flow to the surface and those that are too dense and cannot reach the surface. X_{CO2} indicates the mole fraction of CO_2 in water. Waite et al. [1] report X_{CO2}= 0.053±0.001. The break in the upper two curves is at the pressure CO_2 starts to come out of solution.

Postberg et al. [2] model the eruptions that might result from the water, gases, salts, and all other chemicals that our circulation model provides. Near the surface some gas and much of the heat are lost from the water. With the loss of heat the water becomes relatively cool and denser. It absorbs the remaining bubbles. The cold water, now denser than the ice, descends via fractures or other defects in the ice, and percolates down to the "ocean". It is during this period when the water is in intimate contact with the ice and chemical interactions are possible. While the formation of the briny "ocean" was envisioned as due to the exclusion of non-water chemical species from the ice as it froze [8], yielding relatively pure ice, a number of mechanisms permit a variety of organic and inorganic species to be present in the ice. For example clathrate hydrates could form directly at the freezing front or simple adsorption onto the freezing ice might take place where clathrate is not stable. Another mechanism involves the irregular advance of the freezing ice. Under proper geometric conditions, pools of brine could be mechanically trapped in the ice and frozen later. The downward percolation of briny water which occurs in our model provides another mechanism for mechanical trapping and chemical alteration by making a large volume of the ice available for these interactions. While Waite et al. [1] note that "ammonia [together with methanol and salts] acts as an antifreeze that permits the existence of liquid water down to temperatures as low as 176 K", this is just a conjecture because we do not know the concentrations in solution and thus relevant temperature for Enceladus.

As the briny water percolates down it thermally equilibrates with the local ice. If tidal dissipation [9] or other mechanisms is produce heat, it can be picked up by the water and carried to the "ocean". Thus, in these regions the heat will be flowing downward. An active process such as this could be very effective in keeping the "ocean" reservoir from freezing.

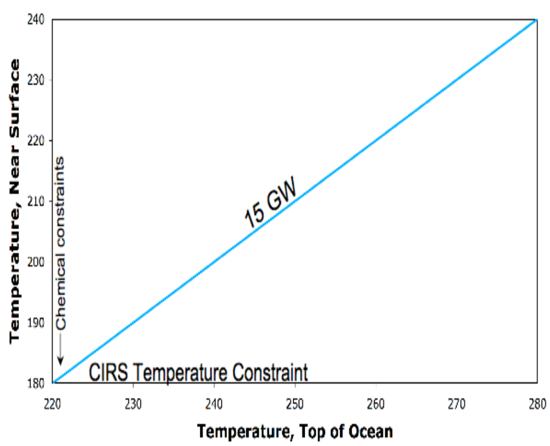

Fig. 2. Temperatures needed for adequate heat flow. The abscissa is the temperature of the water at the top of the reservoir ("ocean"). The ordinate is the lowest temperature the water reaches (after losing heat near the surface). The curve shows the combinations of temperatures that deliver 15 GW to the surface for a flow rate of 90 m^3sec^{-1}. If the flow is half that, then 7.5 GW would be delivered. Matching the 15 GW line is equivalent to assuming that the circulation model supplies all of the observed heat. This would not be necessary if other mechanisms produce some of the heat near the surface (e.g. Nimmo, et al. [10]).

Bubbles serve a number of purposes in the model. When the water ascends the formation of bubbles reduces the column density and provides the buoyancy needed to bring the water up to the surface. In the reservoir directly feeding the plumes, bubbles reaching the surface of the water can pop and throw a very fine spray. Some of these very small droplets of brine exit with the plume gas and are the source of the observed, salt-rich dust particles [2]. As the bubbly brine looses its heat near the surface, the gas in the bubbles dissolves back into the water. Now colder and without bubbles, the brine is denser than the ice and percolates downward along fractures and defects in the ice crust, returning to the ocean.

References: [1] J. H. Waite Jr et al., *Nature, 460*, 487-490 (2009). [2] F. Postberg et al., *Nature, 459*, 1098-1101 (2009). [3] S. W. Kieffer et al., *Science, 314*, 1764-1766 (2006). [4] C. Howett, J. R. Spencer, J. Pearl, M. Segura, *Bull. Am. Astron. Soc., 41*, 1122 (2009). [5] O. Abramov, J. R. Spencer, *Icarus, 199*, 189-196 (2009). [6] G. D. Crawford, D. J. Stevenson, *Icarus, 73*, 66-79 (1988). [7] S. L. Murchie, J. W. Head, *LPS XVII,* 583-584 (1986). [8] M. Y. Zolotov, *Geophysical Research Letters, 34*, L23203 (2007). [9] G. Tobie, O. Cadek, C. Sotin, *Icarus, 196*, 642 (2008). [10] Nimmo, F., et al., *Nature, 447***,** 289-291, (2007).

This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration, and for JIL under the program "Incentivazione alla mobilita' di studiosi straineri e italiani residenti all'estero" of Italy.