ENCELADUS' GAS BUDGET AND OCEAN TEMPERATURE. D. L. Matson[1], T. V. Johnson[1], A. G. Davies[1], J. C. Castillo-Rogez[1],and J. I. Lunine[2], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91101, dmatson@jpl.nasa.gov, [2]Department of Astronomy, Cornell University, Ithaca, NY 14853.

Introduction: The relationships between water, carbon dioxide and heat in Enceladus are used to obtain the temperatures of water in the plume-formation chambers and in the subsurface ocean. These gas budget calculations are carried out in the context of the hydrothermal circulation hypothesis described by Matson et al. [1].

Background: Enceladus' plumes are composed of gases and small particulate matter (called "dust"). Waite et al. [2,3,4] report the gas composition measurements. Dust particle compositions have been reported and discussed by Postberg et al. and Schmidt et al. [5,6]. Of particular importance is their conclusion that this material comes from a subsurface ocean. The hydrothermal circulation described by Matson et al. [1] brings heat and materials up from the ocean to supply the plume-formation chambers and the surface heat flow [7]. Schmidt et al. and Postberg et al. [5,6,8] describe the detailed operation of the plume chambers and vents.

Calculation of Ocean Temperature: We use the gas content of the erupting plumes to estimate the amount of heat needed for plume operation and from that the rate at which ocean water is flowing through the plume chambers. The gas in the plumes is 90 percent water vapor with an estimated eruption rate of ~300 kg s^{-1} ($m_{plume\ eruption\ rate}$) [9]. Most of the vapor comes from liquid water because it has a higher evaporation rate relative to sublimation of the colder ice. The energy needed to supply the latent heat of vaporization in the chamber is available locally, and is obtained by reducing the temperature of the water. This energy and any lost sensible heat is replenished as ocean water flows through the chamber. Producing a kilogram of water vapor requires 2.26 x 10^6 J. Thus the observed vapor eruption uses ~6.8 x 10^8 W of heat. This heat requirement is met by the water-flow rate ($F_{ocean\ water\ flow\ rate}$, kg s^{-1}) times the water's change in temperature (ΔT, K) as it arrives from the ocean and passes through the plume chambers. This plume-water-vapor constraint can be expressed as

$$H = F_{ocean\ water\ flow\ rate}\, c_{sp}\, \Delta T \qquad \text{(Eqn. 1)}$$

where c_{sp} is the specific heat of water.

The abundance of CO_2 in the plumes, X_{CO2}, is ~0.05 mole fraction [2]. We assume that all of the gas in the water is evaporated when the water is exposed to the near-vacuum pressures in the plume chambers. (Note that this assumption differs from that of Matson et al. [1] who assumed an ocean temperature of 0 ºC and found that water in the plume chambers lost most if not all of its gas. In the present work we assume that water passing through plume chambers loses all of its gas and then find the ocean temperature.) Based upon consideration of the conditions necessary to buoyantly erupt ocean water to the surface, Matson et al. [1] found $X_{CO2\ ocean\ water}$ ~1.7 x 10^{-4} mole fraction. The amount of ocean water required to supply CO_2 in the plumes is given by

$$F_{ocean\ water\ flow\ rate} = m_{plume\ eruption\ rate}\,(X_{CO2\ plume} / X_{CO2\ ocean\ water}) \qquad \text{(Eqn 2)}$$

From Eqn 2, the total flow for all of the plume chambers amounts to ~8.8 x 10^4 kg s^{-1}. Given this ocean-water flow rate, we can use the plume-water-vapor constraint (Eqn 1) to calculate that the resulting temperature change is ~2 K. The transfer of the large amount of heat to support the plumes and observed surface thermal anomalies indicates that the ocean water is in contact with the ice. The freezing point of seawater is ~-2 ºC and that and the large flow rate suggests that the downwelling water is also ~-2 ºC. With ΔT~2 K, the upwelling ocean water being supplied to the plume chambers and the thermal anomalies must have a temperature of ~0 ºC. Given the large flow rate of ~10^5 kg s^{-1}, it is not thought that much heat will be lost from the bulk of the water as it comes up from the ocean. Thus ~0 ºC is a reasonable estimate for the ocean temperature.

Summary and Implications: The operation of the plumes draws heat from water in the plume chambers. This heat is replenished by circulating ocean water that is cooled ~2 K. Water in contact with surface ice and leaving the plume chambers has a temperature near -2ºC, the freezing point of seawater. This suggests that water arriving from the ocean has a temperature of ~0 ºC.

Maintaining Enceladus' ocean at ~0 ºC requires a source of heat. This source is unknown. Tyler suggests that sufficient power may come from dissipation in the ocean [10,11,12,13]. He argues that the ocean could form a cavity for Rossby-Haurwitz waves excited by obliquity tides. However, Chen and Nimmo do not expect the obliquity to be sufficient for this [14]. Meyer and Wisdom noted that obtaining the needed amount of tidal heating conflicts with Enceladus' current orbital state [15]. The tidal dissipation estimate by Meyer and Wisdom is a direct function of

Saturn's dissipation factor, Q. Recent astrometric observations have led to new estimates of Saturn's Q that are lower and allow much more dissipation [16]. These new developments offer hope that the source of heat may soon be found.

Acknowledgement: This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References: [1] Matson, D. L. (2012) *Icarus* submitted. [2] Waite, J. H., Jr., et al. (2006) *Science 311,* 1419-1422. [3] Waite, J. H., Jr., et al. (2009) *Nature 460,* 487-490. [4] Waite, J. H., Jr., et al. (2010) COSPAR, Bremen, Germany, Abstract # B03-0018-10. [5] Postberg, F., et al. (2009) *Nature 459,* 1098-1101. [6] Schmidt, J., et al. (2008) *Nature 451,* 685-688. [7] Spencer, J. R., et al. (2006) *Science 311,* 1401-1405. [8] Schmidt, J., et al. (2010) *BAAS 42,* 977. [9] Hansen, C. J., et al. (2006) *Science 311,* 1422-1425. [10] Tyler, R. (2008) *Nature 456,* 770-772. [11] Tyler, R. (2009) *GRL 36,* L15205. [12] Tyler, R. (2010) *J. Cosmology 5,* 959-970. [13] Tyler, R. (2011) *Icarus 211,* 770-779. [14] Chen, E. M. A., Nimmo, F. (2011) *Icarus* submitted. [15] Meyer, J., Wisdom, J. (2008) *Icarus 198,*178-180. [16] Lainey, V., et al. (2010) *EPSC Abstracts 5,* 123.