Identification of Possible Heat Sources for the Thermal Output of Enceladus

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Abstract

We have calculated the amount of radioactive heat production (RHP) that could possibly prevent the postulated underground ocean of Enceladus from freezing. An internal heat source is necessary to justify the observed heat output from Enceladus and to allow the tidal dissipation heating models to work. Also based on the terrestrial evidence, we have assumed that the most common radiogenic element that can produce such internal heat is $^{238}$U. Our results show that a minimum amount in the range 38.10–76.59 ppm of $^{238}$U, averaged over the whole mass of Enceladus, is necessary to obtain the required RHP. The range of values increases to 63.60–127.70 ppm if we consider only the mass of the rocky portion and 2890–5775 ppm if we consider the mass of the rock + ice portion of Enceladus just below the southern polar area. Even in the latter case, the concentration of uranium is still well below the amount found in high-grade ore on Earth.

Unified Astronomy Thesaurus concepts: Saturnian satellites (1427); Tidal interaction (1699); Planetary interior (1248)

1. Introduction

Enceladus is a moon of Saturn that shows intriguing aspects regarding its current geologic activity. The endogenic thermal output of Enceladus is mostly coming from the funiscular terrain between the tiger stripes located in the southern polar terrain (Spencer et al. 2009; Howell et al. 2011; Bland et al. 2015). Initial measurements of the thermal output obtained by Cassini yielded $\sim 5.8 \pm 1.9$ GW (Spencer et al. 2006), which was raised to $15.8 \pm 3.1$ GW by subsequent high spatial resolution measurements by the Cassini Composite Infrared Spectrometer (CIRS; Howell et al. 2011; Spencer & Nimmo 2013). Equilibrium tidal heating can only account for 1.1–1.2 GW (Meyer & Wisdom 2008; Travis & Schubert 2015). Another model pushes up to 3–7 GW, but it is still insufficient to account for the whole thermal output (Roberts & Nimmo 2008). Shear heating may have provided a similar range of thermal output between 4 and 8 GW (Nimmo et al. 2007), also insufficient to account for the whole thermal output. It is evident that a discrepancy exists between the detected thermal output and the one produced by tidal and/or shear heating. The source of the thermal output is still controversial between tidal dissipation heating (TDH), shear heating, and radioactive decay (Meyer & Wisdom 2007; Nimmo et al. 2007; Schubert et al. 2007). A combination of both tidal and radioactive heating (Czechowski & Leliwa-Kopytynski 2005) with a liquid water layer bearing hydrocarbons in dilute solution was proposed as a possible source for the plume in the south polar region (Matson et al. 2007; Postberg et al. 2008). The presence of sodium (chloride, carbonate, and bicarbonate) salts (Postberg et al. 2009, 2011) in the liquid water layer would ensure a positive coefficient of thermal expansion (Goodman et al. 2004; Choblet et al. 2017). Furthermore, potassium should also be present because, chemically, it behaves similarly to sodium, it is present in lower amounts due to its lower abundance in the universe, and it has been reported as a trace element by Postberg et al. (2009, 2011). This also means that radiogenic heating is inevitably taking place, as this element always contains a certain quantity of $^{40}$K as a radioisotope. These salts would create stratifications of fluid layers behaving like a solid boundary, across which heat coming from uprising plumes would be transferred via thermal conduction (Goodman et al. 2004). Sodium salts remain dissolved in the liquid (Zolotov 2007), and the salty solution that is not freezing on top of the ocean tends to sink and form plumes descending turbulenty, which would rise convectively upon heating from below and then escape through the fractures present in the icy crust to be detected from orbit (Postberg et al. 2009). Serpentinization has also been suggested as a possible heat source (Sekine et al. 2015), but, if generated at global rate of $7.5$ GW, it would be depleted in $\sim 40$ Ma (Travis & Schubert 2015). Much effort was dedicated to finding possible ways to enhance the TDH in order to reach the observed thermal output, the most common of which relies on the presence of a subsurface ocean. The 0.8% ammonia content detected in one of the plumes implies its possible presence in a hypothetical subsurface ocean acting as “antifreeze” (Waite et al. 2009). Higher concentrations (i.e., 15 wt%) of ammonia in the subsurface ocean would founder the overlying ice shell, eventually exposing the ocean freezing to space again (Roberts 2015). Tidal heating can be significantly enhanced by the resonance of subsurface oceans thinner than 1 km (Matsuyama et al. 2018); however, such a thickness is much lower than the values of 10–40 km inferred from gravity and topography constraints (Iess et al. 2014; Hsu et al. 2015). Other estimates bring it up to $\sim 40–72$ km (Patthoff & Kattenhorn 2011) or $\sim 36–90$ km of thickness for the subsurface oceans (Olgin et al. 2011). On the other hand, depending on the ice grain size, a thicker ice shell, up to $\sim 100$ km, might be necessary to trigger or continue convection (Barr & McKinnon 2007). While previous models placed the depth of the subsurface ocean at $\sim 90$ km (Mitri & Showman 2008), other constraints suggest a subsurface liquid reservoir located at various depths, from 350 m to $>1$ km of depth.
An ocean shallower than 10 km was thought to fit the surface temperatures detected by the CIRS, depending on the model assumed (Tyler 2009). The latest models conclude that a liquid subsurface ocean should be located under a 20–35 km thick ice shell for a total thickness of 55–70 km (Travis & Schubert 2015), or a total thickness of 21–67 km under an ice shell 14–26 km thick (Van Hoolst et al. 2016). Nearly the entire range of these thicknesses was already considered in the TDH modeling of Roberts & Nimmo (2008), but the main problem is that any subsurface ocean will freeze if there is not greater heat production in the core than the one removed at the base of the ice shell. The same problem affects the TDH model of Travis & Schubert (2015). For this reason, we wish to pay more attention to a simpler explanation based on additional radiogenic heating (than previously thought) supporting the subsurface ocean in order to fit the TDH and the observed thermal output. The latter option was not considered by Roberts & Nimmo (2008) based on their exclusion of a different composition of the core of Enceladus than chondritic. We also support our choice with the fact that no significant change in thermal output was observed among two different Cassini flybys (18 months), suggesting that a steady-state heating process might be at work inside Enceladus (Abramov & Spencer 2009). Relaxing the steady state is also one of the assumptions at the basis of the TDH model by Roberts & Nimmo (2008), which is not supported, at least on the timescale of the current observations. Indeed, we feel that the overall discussion of the missing source of the observed thermal output would benefit by considering additional sources other than tidal heating. Additional heat coming from the core would, by the way, be much needed to make the TDH models work. Although the observation of a possible steady-state thermal output suggests that radiogenic heating might be necessary to keep Enceladus warm (Matson et al. 2007; Schubert et al. 2007; Travis & Schubert 2015), the hypothetical presence (and possible location) of radiogenic elements necessary to maintain the observed heat flux was certainly mentioned but never estimated. One could perhaps speculate that the core is not completely symmetrical and that the metal core is somewhat displaced toward the northern hemisphere (Showman et al. 2013). Silicates, which are known to accumulate higher amounts of radioactive elements such as U, Th, and K (Wendle 1998), might be displaced toward the southern pole, leading to an anomalous concentration of radioactive elements in this region. Or the core could simply be symmetrical, with a classic decreasing amount of metal and increasing amount of rock as we move outside where the lithophile radiogenic elements like uranium would be more concentrated. It would not be surprising if such a concentration were present in the rocky portion of the core located beneath the south pole, given that the observed thermal output comes mainly from there. In the case of either asymmetry or symmetry of the core, our results would not be affected because the heat flow would emanate directly from the radiogenic source toward the south pole independently from the shape of the core. At last, it would also be interesting to have a better understanding of the possible composition of the generic word “rock,” which is often used with an undefined meaning in the literature describing the internal structure of Enceladus. We explore the possible types and amounts of radiogenic elements to see whether their presence might explain the observed discrepancy in the thermal output and thus support the various TDH models.

2. Method

Based on the radioactive heat production (RHP) data collected in terrestrial samples (Abbady 2010) and the heating rates in CI chondrites in the early solar system (Barr & Canup 2008), we calculate the possible concentration of radiogenic elements that Enceladus should have to justify the steady state of the current heat output observed from Cassini data. In order to estimate the RHP, we have subtracted the tidal heating fraction from the current whole thermal output that includes all of the heat sources of Enceladus. According to the various estimates mentioned in the previous section, we have considered a contribution of radiogenic heating in the wide range between 7 and 14 GW. Such a range is consistent with the missing balance between the total observed thermal output of ∼15 GW and the ∼1–8 GW proposed by Meyer & Wisdom (2008) and Roberts & Nimmo (2008), respectively. We do not consider the entire range up to 25 GW of the TDH model proposed by Roberts & Nimmo (2008) because (a) it is beyond the observation of a steady-state thermal output up to ∼15–16 GW, (b) such a high thermal output cannot be sustained by the TDH model at the current eccentricity of Enceladus (Spencer et al. 2006), and (c) it comes from an underestimation of the present-day radiogenic heating (PDRH), which is based on the possible misconception of a chondritic composition for Enceladus. Despite the TDH model of Travis & Schubert (2015) trying to cover the whole range between 8 and 16 GW, it is affected by the same problem as the Roberts & Nimmo (2008) TDH model, that is, the need for constant radiogenic heating preventing the freezing of the ocean if insufficient TDH is generated in the ice shell. Travis & Schubert (2015) placed a constraint of minimum constant radiogenic heating of 7.5 GW to keep the ocean layer warm. Choblet et al. (2017) raised this value to 10 GW to keep the hydrothermal processes active. Therefore, like Travis & Schubert (2015), we assume constant radiogenic heating coming from the (more external) rocky part of the core between 7 and 14 GW to take into account all of the various possibilities. If the statement of Travis & Schubert (2015) that “the 50 × PDRH (15 GW) power level would be sustained for a short period of time in the very early history of Enceladus (the first 10 Ma or so)” was true, we would not see any activity at all but just traces of extinct activity like that observed on other parts of Enceladus or other moons of the outer solar system. In any case, we have even considered an extreme and hypothetical case in which the PDRH accounts for only 1 GW of the total thermal output. The early activity of short-lived radiogenic elements like 26Al or 60Fe would be strong enough to completely melt Enceladus, as was the case for Mars (Leone et al. 2014), so the decay of 238U is what really matters in the long term. We only need to see if a PDRH contribution between 7 and 14 GW could be justified from the geological point of view. In order to have a more complete picture of the RHP, we have also included the decay of Th and K to 238U, the contributions of 238U, 232Th, and 40K being the most geologically significant on Earth (Abbady & Al-Ghamdi 2018). The best candidate for a radiogenic element is 238U, also due to its half-life of 4468 Ma (Billström 2008), which dates back to the early history of the solar system and thus of Enceladus as well. Also, with its 99.72% of abundance, 238U is the most...
Table 1

Concentration of the Radioactive Elements Necessary to Sustain the Thermal Output of Enceladus

|        | $H_i$ (GW) | $H_o$ (GW) | $U$ ppm | $Th$ ppm | $K$ (kg t⁻¹) |
|--------|------------|------------|---------|----------|--------------|
| 1.00   | 0.60       | 5.10       | 14.57   | 21.00    |
| 1.68   | 1.00       | 8.80       | 25.14   | 21.00    |
| 7.00   | 4.21       | 38.10      | 108.85  | 21.00    |
| 7.50   | 4.51       | 40.85      | 116.71  | 21.00    |
| 11.64  | 6.99       | 63.60      | 181.71  | 21.00    |
| 12.48  | 7.50       | 68.20      | 194.85  | 21.00    |
| 14.00  | 8.42       | 76.59      | 218.82  | 21.00    |
| 23.30  | 14.00      | 127.70     | 364.85  | 21.00    |
| 23.41  | 14.07      | 127.70     | 364.85  | 50.00    |
| 7.11   | 4.28       | 38.10      | 108.85  | 50.00    |
| 14.11  | 8.48       | 76.59      | 218.82  | 50.00    |

Note. The values of concentration are calculated over the RHP generated by the entire mass of Enceladus ($H_i$) or just its rocky portion ($H_o$).

common isotope of natural uranium on Earth (Bonotto et al. 2001), which is the main active body of the solar system with internal heating not depending on tidal forces like those that Jupiter or Saturn may apply. The RHP, $H$ in this case, is calculated according to Rybach (1976), Norden & Förster (2006), and Abbady & Al-Ghamdi (2018):

$$H = \rho(9.52 \text{ U} + 2.56 \text{ Th} + 3.48 \text{ K})10^{-5}.$$

Here, $H$ is the generated heat expressed in $\mu$W m⁻³, $\rho$ is the rock density, and $U$, $Th$, and $K$ are the contents of uranium, thorium, and potassium, respectively. The amount of uranium that would be expected in a chondritic composition would be approximately in the range 0.01–0.12 ppm, being a 3:5:1 relationship of concentration between 238U and 232Th (Nittler et al. 2004). There are variable relationships in the literature, ~3:1 (Hazen et al. 2009) or 3.9:1 (Degueldre & Joyce 2020), but we choose the ratio 3.5:1 as an average estimate. We then calculate the heat generated in $\mu$W/t by dividing $H/\rho$ and the heat generation from the total mass of Enceladus. As result, we provide the heat generated from the total mass of Enceladus, $H_o$, and the heat generated only from its rocky mass, $H_r$. This could be justified by the fact that the accumulation of radiogenic elements like uranium may occur not only in rocks but also in water, as observed on Earth (Wendle 1998).

Leakage of uranium from rock to water was observed at the contact point between rock and water; the concentration of uranium in water decreases with increasing distance from the source (Ivanovich et al. 1991; Paces et al. 2002). Then, convective flows in the underground ocean can transport minimum amounts of uranium from the water to the overlying ice sheet. We show the results in Table 1. At last, we have provided the heat generation from the mass of Enceladus related to just the polar area where the tiger stripes are active.

3. Results

According to our results, a minimum concentration of 38.10 ppm or a maximum concentration of 127.70 ppm (as 1 ton = 1,000,000 gm) of uranium would be necessary to generate our assumed PDRH of Enceladus. These concentrations would be the extreme ends to generate 7 and 14 GW, respectively. In between, values would be included between 63.60 and 76.59 ppm (Table 1). The concentration rises to the maximum range of 2890–5775 ppm if we consider just the mass (1.44 × 10¹⁵ m³) of the southern polar area of Enceladus. Even in the extreme and hypothetical case of 1 GW of PDRH, the required concentration of 238U would be in the range 5.1–8.8 ppm. The total contribution of potassium is less significant among the three radiogenic elements; even (more than) doubling its concentration does not provide a significant contribution to the thermal output. In fact, the concentration of uranium is the determinant factor for the production of the possible PDRH of Enceladus observed by the Cassini spacecraft.

4. Discussion

It was pointed out that Enceladus may have had a higher eccentricity in the past, suggesting the possibility of an episodic TDH that could occur on a 100 Myr cycle, which would allow PDRH to be sufficient (Shoji et al. 2014). It was even suggested that an extreme heat flux would have been present in the past on the basis of the deformation of some craters by viscous relaxation of water ice under the effect of an elevated heat flow; this higher heat flow would have activated other areas that now appear inactive (Bland et al. 2012).

Although we do agree with the possibility that other areas of Enceladus may have been active in the past, the idea of a higher thermal output in the past by a change in the steady state, supported on the basis of the relaxation of the craters, is objectively hard to support. First, as Shoji et al. (2014) admitted, tidal heating has the effect of reducing the eccentricity, and it might be hard to demonstrate that the eccentricity of Enceladus was higher in the past. Actually, the studies of Meyer & Wisdom (2008) show how the eccentricity of Enceladus is in equilibrium on long (i.e., gigayear) timescales, much higher than the 100 Myr timescale suggested above. Furthermore, in the inactive areas distributed over the whole face of Enceladus, there is objectively no sign of catastrophic or at least massive cryovolcanism that could justify a higher thermal output in the past. Second, the deformation of the craters observed by Bland et al. (2012) can also be explained by a small episode of flooding by cryolava that modified the rims and filled the craters (Kite & Rubin 2016). A similar mechanism by which hot lava deforms rims and fills craters on Mars (i.e., Leone 2016, 2017; Gasparri et al. 2020) or the Moon (i.e., Cruikshank et al. 1973) essentially gives a similar geomorphological result. Indeed, resurfacing was suggested in the active areas of Enceladus due to the scarcity of craters (Porco et al. 2006; Schubert et al. 2007).

In this context, the observations of steady-state thermal output from Enceladus (Figure 1) are perfectly consistent with an endogenic heat source (Abramov & Spencer 2009), higher than the external one provided by equilibrium tidal heating (Meyer & Wisdom 2008). The presence of 238U in the interior of Enceladus would be a consistent explanation.

Now the big question is whether such a wide range of concentrations of 238U would be plausible in a body thought to have chondritic composition (Roberts & Nimmo 2008; Sekine et al. 2015), although this chondritic composition has been not at all certain since the beginning (Peale 1999). Other models have already concluded that Enceladus could be composed of mixtures of rock, metal, and ice with a silicate mass fraction ranging from 52% to 60% (Gerald Schubert et al. 2007) or at least a rocky fraction that should be able to contain the radiogenic elements necessary to heat Enceladus from the interior (Matson et al. 2007). We have just seen how the
concentration of radiogenic elements, uranium in particular, necessary to justify the assumed PDRH are not exactly those observed in a chondritic composition. Actually, the concentration required is much higher than that observed in a chondritic composition, even higher than that (0.87–8.17 ppm) observed in trachytes or phonolites (Oversby et al. 1971) and more similar to those (10–200 ppm) observed in sedimentary rocks on Earth (Rothbaum et al. 1979). Surely above than the average concentration (2.7 ppm) observed in the continental crust of Earth (Wendle 1998; Hazen et al. 2009). A concentration comparable to volcanic rocks on Earth, 5.1–8.8 ppm (Table 1), would produce only 1 GW of PDRH, which would be insufficient to keep the subsurface ocean warm, as estimated by Travis & Schubert (2015) and Choblet et al. (2017). Our results open new scenarios, or maybe support previous ones, for the internal structure of Enceladus. Certainly, the amount of radiogenic elements necessary to reach the “missing” quota of nontidal thermal output does not play in favor of a chondritic composition. Actually, it leans toward the rockier composition of the Schubert et al. (2007) model for the internal structure of Enceladus, unless we are willing to accept the idea of such an unusual concentration of radiogenic elements in a chondritic composition. A concentration between 63.60 and 76.59 ppm, or as much as 2890–5775 ppm, in rocky material located just
under the south pole of Enceladus would be required to maintain the observed thermal output. Such a concentration becomes even more unusual when we consider that the heat generation decreases with time due to the decay of the radiogenic elements (Schubert et al. 1980). Now the question of whether such a concentration could be perfectly plausible on Enceladus when compared to those observed on Earth gets a positive answer only when we consider sedimentary rocks or high-grade ore deposits (10^4–10^5 ppm) formed by magmatic hydrothermal activity (Hazen et al. 2009). However, the distribution of radiogenic elements like uranium and thorium in the primordial protoplanetary disk was homogeneous at the beginning, then heterogeneities formed in a later stage when a partial transfer of U occurred between gaseous and solid phases (Andersen et al. 2017). These heterogeneities may have formed local concentrations of U in the outer solar system. This hypothesis finds additional support in the active cryovolcanism of Enceladus and the widespread evidence of past cryovolcanism in the outer solar system (Geissler 2015). The evidence of the active “tiger stripes” located exactly around the south pole of Enceladus, while there is no other significant sign of ongoing cryovolcanic activity elsewhere on the surface aside from relics of past activities, supports the possibility that such an unusual concentration of uranium may still exist inside Enceladus. Thus, given that it is reasonable to think that such PDRH could not begin only in recent times, the possibility that the concentration of radiogenic elements was highest just below the south pole since the initial formation of Enceladus can find good support in the current observations. Another good question would be, where is such an unusual concentration of radiogenic elements located? Being a lithophile element, uranium preferentially occurs in the more acidic and thus differentiated igneous rocks on Earth, where hydrothermal processes produce high concentrations of U and Th (Bonotto et al. 2001; Hazen et al. 2009). Hydrothermal processes implying water–rock interactions have been postulated on Enceladus (Hsu et al. 2015; Sekine et al. 2015; Choblet et al. 2017; Waite et al. 2017), so it would not be difficult to imagine and/or justify a concentration of 238U in the upper part of the core. This also confirms that the internal structure of Enceladus may have been subject to differentiation since its early formation, maybe already starting with the early activity of 26Al (Schubert et al. 2007). Thus, the rocky part of the core may have been differentiated into a more internal mafic composition and a more external acidic composition. A logical answer would thus be that the presence of 238U should be concentrated at least in the most acidic part of the rocky portion of the core, which should be located just below the ice shell. In this case, according to the available models of internal structure of Enceladus by Schubert et al. (2007) and Travis & Schubert (2015), the rock–ice boundary might be located at around 90–96 km of depth, where the heat released by the radiogenic elements would form and sustain the liquid layer interpreted to be the underground ocean of Enceladus. We have already seen how thick is this ocean it is only matter of numbers but it would not change the mere substance of fact that it would rapidly transfer the heat to the surface by means of convection inside it, exactly as the fire under a boiling pan of water would do. Furthermore, the PDRH generated in the upper core would contribute to keeping warm that subsurface ocean that is so necessary to sustain the TDH models.

5. Conclusions

The undeniable evidence of the ongoing thermal activity of Enceladus requires heat sources that cannot be justified by TDH alone. An internal RHP is necessary to keep the subsurface ocean warm in order to enhance and thus take into account the TDH contribution. The amount of RHP required to keep the subsurface ocean warm is at least above 7.5 GW, which can be produced by a concentration of 238U, 232Th, and 40K of 68.20, 194.85, and 21 kg t^-1, respectively, in the outer portion of the core. The concentration of 238U rises to a range of 2890–5775 g t^-1 (or ppm) if we consider only the mass of the southern polar area of Enceladus. Such a concentration might appear unusual in a body of chondritic composition and even of mafic composition, but it is dwarfed by the concentration (10^4–10^5 g t^-1, or ppm) found in high-grade ore deposits on Earth. Compared to these concentrations, even a concentration in the range 38.10–127 g t^-1 (or ppm) could be plausible for Enceladus. We therefore conclude that the observed thermal output, whatever its total sum of contributions would be, still needs an RHP in the range 38.10–76.59 g t^-1 (or ppm) if we include the rocky portion and the ice shell. The range of values increases if we consider only the rocky portion, 63.60–127.70 g t^-1 (or ppm) for 7 and 14 GW, respectively. The composition of the rocky portion of the outer core, which is in direct contact with the external ice shell, could be formed by differentiated igneous material of likely acidic (granitic) composition. A TDH mechanism would not work without this internal RHP, Enceladus would appear inactive like other moons of the outer solar system.

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