

# Radiolytic impacts of energetic electron irradiation on Enceladus and Mimas

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## Abstract

Episodic overturn of the south polar terrain on Enceladus would convey radiolytic oxidants from surface irradiation by Saturn's inner magnetospheric electrons to the putative underlying polar sea and contribute to CO<sub>2</sub> and other gas production driving the visibly active cryovolcanism. Low duty cycle of active episodes below 1 – 10 percent would raise the relative importance of the continuous radiolytic chemical energy input for mass and heat outflow, e.g. as compared to heating by gravitational tides. The "Pac-Man" thermal anomaly on Mimas most likely arises from leading-trailing asymmetry of electron irradiation and resultant radiolytic processing of the moon ice to a few centimeters of depth. The Mimas thermal anomaly distribution suggests a relatively stable surface unmodified by Enceladus-like geologic overturn or cryovolcanic activity. In both cases, the heavily irradiated skin depth corresponds to the sensible thermal layer probed by Cassini infrared measurements. Neutral gas and dust emissions from Enceladus limit energetic ion and plasma electron fluxes in the inner magnetosphere, thereby governing the irradiation of Mimas and other Saturn moons.

## 1. Introduction

Energetic electrons are a dominant component of surface irradiation at Saturn's icy moons Enceladus and Mimas. Electron acceleration during diffusion into Saturn's inner magnetosphere produces higher number and energy fluxes at Mimas, both moons being heavily irradiated to thermally and optically sensible centimeter depths over 10<sup>4</sup> – 10<sup>6</sup> years [1].

Dissociation of water ice and other surface molecules by electron-induced radiolysis leads to accumulation of chemical oxidants such as O<sub>2</sub> and H<sub>2</sub>O<sub>2</sub>, which can further react with endogenic NH<sub>3</sub>, CH<sub>4</sub>, and other hydrocarbons to form volatile gases such as N<sub>2</sub> and CO<sub>2</sub>. Cassini observations have shown that the

active cryovolcanic emissions of ice grains [3] and water vapor from Enceladus are accompanied mostly by CO<sub>2</sub> but also at comparable ~1% levels by CH<sub>4</sub> and NH<sub>3</sub> [6]. The radiolytic oxidants are not detectably present in the emissions but may have been consumed below the surface by oxidation processes before cumulative pressure of the CO<sub>2</sub> and other accumulated oxidation product gases drive out the water vapor [1]. Possibly all of these non-H<sub>2</sub>O ejecta are from primordial sources, e.g. accretion of cometary material [6], but presence of both the reactants and the products of radiolytic oxidation could also be consistent with still active chemistry driven in part by surface irradiation. Chemical reaction rates would be exponentially enhanced in the presence of strong thermal gradients associated with a south polar (if not global) sea located kilometers below the ice surface. Compositions of the emitted vapor [6] and ice grains ejected into the E-ring [4] are consistent with modern presence of such a sea, although all evidence for the sea is not yet conclusive.

Mimas appears to present a more passive example of surface irradiation effects. The region of high thermal inertia, measurably colder than expected in daytime and warmer at night, is concentrated in the leading hemisphere in a broad lens-shaped surface region preferentially irradiated by energetic electrons drifting opposite to the prograde direction of magnetic corotation at energies above 1 MeV [5]. Although radiolytic chemistry likely plays a strong role in creation of the thermal anomaly, the process has not yet been explained.

Finally, there is clearly a connection between outgassing and E-ring formation by Enceladus, and the inner magnetospheric environment irradiating Mimas. Plasma electron and suprathermal ion fluxes are depleted in the inner magnetosphere, apparently due to energy loss in the gas and dust from Enceladus. This also depletes the seed population of low-energy electrons that would otherwise be accelerated by inward diffusion to irradiate Mimas.

## 2. Analysis and Conclusions

In this presentation we revisit the underlying assumptions and impacts of the radiolytic cryovolcanism model for Enceladus [1] while also further considering impacts of the similar but even more intense electron irradiation environment at Mimas. The major difference in resultant effects, highly active at Enceladus but only passive in terms on the presumably static thermal anomaly at Mimas, may be traced to very different configurations of the subsurface environments on these two irradiated moons. The south polar terrain of the actively outgassing tiger stripes on Enceladus [3] is clearly younger and resurfaced on million-year time scales, as indicated in part by paucity of impact craters, while there is no such sign on geologically recent activity on Mimas. The existence of the requisite underlying polar sea on Enceladus is still hotly debated, and there is no explanation for the high heat output at the present level of about 15 GW.

A major assumption of the radiolytic model [1] is that accumulated oxidants, which would accumulate globally on Enceladus, would be conveyed downward kilometers in depth below the more mobile south polar terrain to the thermal margins of the putative polar sea. In this environment of thermally elevated chemical activity, reactant fuels such as  $\text{CH}_4$  and  $\text{NH}_3$  would be oxidized to form driver gases to power ejection of the sea water to form the detected flows of vapor and ice grains. To explain the 200 kg/s mass flows of the water vapor we need to accumulate the oxidation gases, assuming constant rates of production, at least ten times longer than durations of high activity episodes for vapor emission. Although the mass flows can be explained by such modest duty cycling, the oxidation processes producing low heat flux up to a few MW are unlikely to account for the observed 15 GW surface thermal emission. We assume that radiolysis could significantly contribute to the mass flows via release of cumulative gas pressure, while the heat to maintain the polar sea in liquid state and to account for the surface heat flux must come from elsewhere, e.g. tidal dissipation in the ice mantle and/or hydrothermal flow of hot (e.g., 647 K at water critical point) high-pressure fluid from the core-mantle boundary. We also of course assume a sufficient supply of reactant fuels that would upwell from the moon interior to the thermal margins of the south polar sea to undergo oxidation.

Our assumptions [1] for the Enceladus model may have been justified by later findings. First, episodic overturn of the south polar terrain on Enceladus at Gyr intervals appears required to account for the evident recent and past resurfacing, as well as for the high present heat output, thus allowing polar sea formation at duty cycle of about one percent (10 Myr) [2]. Secondly, the non- $\text{H}_2\text{O}$  vapor output includes  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{CO}_2$ , and possibly  $\text{CO}$ , [6] as would be expected from complete exhaustion of the radiolytic oxidants to form mostly  $\text{CO}_2$ . If the fuel upwelling rate exceeds the downwelling supply rate for oxidants by tens of percent, then one expects a residual percentage of fuels in the outflow as observed. For Mimas the presence of the presumably stable thermal anomaly is explained by two circumstances. First, the hemispherical asymmetry of more energetic MeV electron irradiation [1,5] produces a more deeply irradiated thermal layer to centimeter depth on the leading hemisphere. Secondly, there is no global or hemispheric sea, or other active subsurface process, to drive resurfacing and disturb the surface distribution of the thermal anomaly on million-year or shorter time scales.

## References

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