Enceladus’s varying imprint on the magnetosphere of Saturn

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The bombardment of Saturn’s moon Enceladus by >20 keV magnetospheric particles causes particle flux depletions in regions magnetically-connected to its orbit. Irrespective of magnetospheric activity, proton depletions are persistent, whereas electron depletions are quickly erased by magnetospheric processes. Observations of these signatures by Cassini’s Magnetospheric Imaging Instrument allow remote monitoring of Enceladus’s gas and dust environments. This reveals significant outgassing variability at the moon, and suggests increased dust concentrations at its Lagrange points. The particle depletions’ characteristics additionally provide key radial diffusion coefficients for energetic electrons and an independent measure of the inner magnetosphere’s rotation velocity.

The importance of interactions between the Kronian magnetosphere and the Enceladus/E-ring system is becoming increasingly apparent. Saturn’s inner magnetosphere is awash with ionized components of water that probably originate at the E-ring (1), and, as recently confirmed, ultimately at Enceladus itself (2, 3). This material significantly alters the inner Kronian magnetosphere, being analogous in several respects to the volcanic material from Io that shapes Jupiter’s magnetosphere. Previous observations of the Enceladus-magnetosphere interaction region by Pioneer 11 and Voyager 2 (4), at 3.945 Saturn radii, Rs, from the planet (5), totaled four crossings of Saturnian magnetic field lines that intersect Enceladus’s orbit, i.e. the moon’s L-shell.

During July 2004 - October 2005, Cassini performed 30 such L-shell crossings, providing a wealth of information on the magnetospheric effects of the moon and the E-ring core through the Low Energy Magnetospheric Measurement System, LEMMS (6) of the
Magnetospheric Imaging Instrument, MIMI. LEMMS employs semiconductor detectors to measure ion and electron fluxes in the energy ranges of 20 keV – 60 MeV and 20 keV – 5 MeV, respectively, usually at a 5.65s resolution. As well as being ion sources, Enceladus and the E-ring are important sinks for Saturnian radiation belt particles. Brown and collaborators (7) consider the consequences of energetic particle bombardment for the moon’s surface chemistry. Here, we report expanded observations of the reciprocal processes: Enceladus’s effect on the energetic particle population, and the remote sensing of significant variability in its outgassing rate. The latter’s changing effect on energetic particles may have significant implications for the inferred age of the moon’s radiation-weathered surface.

Within the radiation belts, low energy magnetospheric plasma corotates almost rigidly with Saturn (8). Within the LEMMS energy range, gradient and curvature drifts are significant: positive ions drift azimuthally in the sense of corotation, and electrons in the opposite direction. Low energy electrons counterdrift slowly enough to maintain a net motion in the corotation direction. However, electrons above the 1.082 MeV resonant energy (9), drift rapidly enough to flow past Enceladus in the direction opposing corotation (Fig. 1). When swept up by Enceladus, ions and low energy electrons therefore form a wake downstream in the corotation flow, leading the moon’s orbital motion, while electrons above the resonant energy form a wake upstream, trailing the orbital motion. At all energies, these wakes, termed microsignatures, continue drifting in the same L-shell and direction, and at the same velocity as the pre-depletion plasma. As microsignatures are primarily refilled by radial diffusion, their longevity mainly depends on the diffusion
rate, with contributions to the signatures’ erosion coming from other magnetospheric processes such as injection events, energy dispersion, and pitch angle diffusion.

Electron microsignatures are expected to be sharp and deep near an electromagnetically inert moon, with radial extents equaling the moon’s diameter. Radial diffusion should broaden and flatten these features with increasing longitudinal separation. High energy electron signatures agree very well with this picture (Fig. 2). Low energy microsignatures however vary considerably with distance from Enceladus, both in profile and depth; several processes could be responsible. Saturn’s magnetic field drapes around the Enceladian atmosphere (10). Low energy electrons sensitive to magnetic field perturbations can be guided around the moon, evading absorption. This forms a narrower, less evacuated wake, possibly asymmetrical due to non-isotropic material outflow from Enceladus. Extended clouds of expelled ice particles and neutral gas would also obstruct electrons. Waves generated by the pickup of fresh ions originating at Enceladus and the E-ring would also increase pitch angle diffusion rates significantly. We suggest that the electron signatures’ breadth and variable depths signify changes on timescales of days or weeks in Enceladus’s ionosphere, the E-ring itself, or the ring’s neutral gas torus. This variability is consistent with other Cassini observations (11) and ground-based E-ring observations (12). Whatever the immediate reason for the signatures’ changes, variability in the Enceladian vents is probably their ultimate cause.

No downstream electron microsignatures have been seen at separations greater than ~80°, indicating large diffusion coefficients at these energies, or considerable flux absorption evasion through ionospheric flow deflection. Tethys microsignatures persist over greater
longitude ranges (13, 14). One possible reason for this difference is the extensive Enceladus/E-ring neutral gas torus, which could diminish the relative depth of the moon’s own microsignature through electron collisions with neutral species. No ion microsignatures were observed, which is explainable by their shallowness: 0.1-1 MeV ions have only a 13-18% probability of collision with Enceladus (15). Upstream energetic electron microsignatures, including those of the close flybys on days 48, 68, and 195 of 2005 (3), consistently behave as if Enceladus is insulating and atmosphere-free. These electrons may have sufficient energy to penetrate the ionospheric obstacle.

Electrons above the resonant energy are therefore lost in a predictable, steady way whereas outgassing levels apparently influence lower energy electron signatures. All the close flybys to date have been upstream of Enceladus; an appraisal of the atmosphere’s influence on low energy electron wakes’ structure requires future close downstream passes.

The close flyby data (Fig. 3), combined with observations of numerous upstream microsignatures, offer a resource to calculate energetic electron radial diffusion coefficients, $D_{LL}$ (16). LEMMS data reveal a narrow energy range (Fig. 3c) within the microsignature where the flux transitions from ~80% of the surrounding value to near-zero. The latter region is the actual energetic electron wake, while the partial decrease marks a reduction in penetrating radiation, i.e. background flux (13). The transition therefore denotes the electron resonant energy, which we find to be $0.75 \pm 0.03$ MeV for 90° pitch angles; the value for rigid corotation is 1.082 MeV.
The resonant energy yields, through a previously-unused technique (18), a cold plasma corotation angular velocity, \( \Omega \) (19), of \((1.39\pm0.03)\times10^{-4}\ \text{rad}\cdot\text{s}^{-1}\). This is \(85\pm2\%\) of the planetary rotation angular velocity (20), the difference almost undoubtedly being due to mass loading of the magnetosphere by ionized neutral gas. The inferred corotation frequency agrees with theory (21), Voyager studies (22), and other Cassini results (23). Using this \( \Omega \) value and the method of (17) yields \(D_{LL}=(3\pm1)\times10^{-8}\text{R}_s^2\text{s}^{-1}\) for energies of 0.98-3.28 MeV. This value is fully consistent, at least in radial extent, with the signature observed by Voyager 2 when 20º upstream of Enceladus (4), and is equivalent to a 1.5 MeV wake refilling in 14.5-15.5 hours.

The above method only sets an upper \(D_{LL}\) limit for low energy electrons, as Enceladus and the E-ring are a complex combined obstacle for these particles, with large variations in profiles responding to changes at both the moon and ring. Using the cleanest signatures (a and b in Fig. 2), we find this upper limit is \((9.0\pm0.2)\times10^{-9}\text{R}_s^2\text{s}^{-1}\). These signatures’ locations suggest a maximum observed wake lifetime of \(~5\) hours for 20-100 keV electrons. If radial diffusion alone refilled these signatures, they should survive for \(~16-20\) hours. Another process, probably ion pickup-related pitch angle diffusion therefore increases the refilling rate.

Enceladus’s microsignatures are time- and longitude-dependent. The moon's longitude- and time-averaged effects on particles’ radial distribution, termed macrosignatures, are also detected. Flux decreases in \(>13\) MeV ions near Enceladus’s L-shell are observed equally well all around the moon's orbit (Fig. 4). The macrosignature’s radial breadth initially suggests that an obstacle more extended than Enceladus is presented to the high-
energy protons; ring material is an established sink for energetic particles (e.g., 24). However, it must be borne in mind that at these energies, the ions’ large gyroradii may, at least partially, be responsible for the wide macrosignatures, i.e. particles whose guiding centers of gyration pass far from Enceladus can still strike the moon. For a macrosignature to be as persistently deep as observed all around Enceladus’s orbit, the proton wakes’ refilling rate must be slower than the particles' rate of reencounter with the moon. As ion gradient and curvature drifts are in the corotation direction, moon re-visit periods are ~1 hour for 10 MeV protons, and ~16 hours for the cold plasma, explaining why no low energy ion macrosignature is observed.

Larger E-ring particles may concentrate near the stable Lagrange points, 60º in longitude from Enceladus. Before Saturn orbit insertion, Cassini crossed Enceladus’s L-shell at 66.0º from the moon (Fig. 4C), and observed an electron pitch angle distribution consistent with particle absorption by dust and/or by neutral gas originating at the dust, as predicted (25). The L-shell was re-crossed a few hours later at 150.8º behind the moon, but showed no 90º pitch angle depletion. The Lagrange point depletion’s confinement to a narrow pitch angle range suggests that dust primarily caused it, not Enceladus itself. This great variation in particle behavior suggests that E-ring dust number density at Enceladus's orbit varies azimuthally. The Lagrange points may be particularly dense regions (26). The large variability in the downstream electron microsignatures suggests that dust may play a major role in their formation. Indeed, their profiles suggest that they decay within a few tens of degrees; Voyager 2 saw no microsignature when only 30º downstream (4). E-ring dust and the associated gas torus may occasionally sustain and
enhance the microsignature profiles by decreasing the electron radial diffusion rate and providing additional sinks for the electrons that remain in the moon’s wake.

References and Notes


5. 1 Rs = 60330 km.


7. R. Brown *et al.*, this issue.


16. The rate at which magnetospheric particles diffuse radially is parameterized by the coefficient \( D_{LL} \). The latter’s value was estimated by fitting a one-dimensional diffusion equation (17) to the LEMMS observations.

18. At the resonant energy, the moon’s Keplerian orbital frequency equals the sum of the energetic particles’ frequencies of corotation, gradient, and curvature drifts. The corotation frequency can be derived by substituting all the other, known values.

19. \( \Omega \) is the angular velocity of the cold plasma that revolves around Saturn approximately in step with the planet’s rotation (9). \( \Omega = 1.637 \times 10^{-4} \text{ rad s}^{-1} \) for rigid corotation with Saturn.


26. We note that similar 90° pitch angle depletions are sometimes observed at Tethys’s orbit (14).

27. R. Tokar et al., this issue.


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Figure 1 An overview of the particle-moon interactions, looking towards Saturn at the orbit of Enceladus, and a broader view providing context. (A) High-energy particles can be lost from the magnetosphere through collisions with the moon’s surface (a), with scattering E-ring dust particles (b), and with neutral gas originating at Enceladus or outgassed from E-ring particles (c). As the corotating plasma’s angular velocity (red arrow; 38.6 kms$^{-1}$) exceeds that of Enceladus (12 kms$^{-1}$), it continuously overtakes the moon (27). (B) Trapped particle bounce motion allows microsignature observations all along magnetic field lines that pass close to Enceladus. Displayed in red is a portion of the volume occupied by energetic electron microsignatures, upstream of the moon in the corotation flow.
Figure 2 Enceladus electron microsignatures observed during Cassini’s first 14 months at Saturn, in normalized counts per second. Panels (a) – (f) show low energy microsignatures, downstream of Enceladus in the corotational flow. Upstream microsignatures, above the resonant energy, are shown in panels (g) – (l), with (j) – (l) showing the three close flybys. The center panel shows each event’s longitudinal separation from Enceladus. Triangles denote observed microsignatures, diamonds show crossings where data gaps or spacecraft rotations preclude interpretation, while squares denote periods during which no microsignature was observed in the available data. In the latter cases, a microsignature was possibly present but was unobservable due to inappropriate LEMMS pitch-angle coverage. The downstream microsignatures’ depths and radial extents are not in accord with their longitudinal separations. Several microsignatures, e.g. (a), are flanked by a broad flux decrease. We note that (a), which has the broadest observed width, of ~16000 km, was observed when Enceladus was definitely outgassing (3). The lack of identified microsignatures between (g) and (h) is probably due to the low fluxes involved: magnetospheric perturbations can easily mask such weak signatures. We note that all events except (e) were located closer to Saturn than expected. This inward electron drift is consistent with flow diversion within a magnetic pileup region (28).
**Figure 3.** Electron fluxes during Cassini’s closest approaches to Enceladus to date, labeled by year and day of year. The views look south onto the equatorial plane (A), and along the corotation flow (B). The coordinate system has X pointing away from Saturn, Y along Enceladus’s orbital motion, with Z completing the right-handed set. Scales are in units of Enceladus radii; \(1R_{\text{En}} = 249 \text{ km}\). (C) Electron spectrogram of the closest, 2005:195 flyby. Almost complete flux depletion is seen above the resonant energy.
**Figure 4** High-energy proton macrosignatures and the E-ring’s variable effects on electron pitch angle distributions. (A) 13-25 MeV MIMI proton fluxes on crossing Enceladus’s L-shell, mapped onto the equatorial plane. The trajectories are plotted in a frame rotating about Saturn with Enceladus. (B) A typical energetic proton macrosignature profile, covering a radial distance of ~0.7 Rs. The edge-to-edge effective absorption region equals the satellite diameter plus four ion gyroradii. This is shown for 25 MeV protons and H$_2$O$^+$ ions (blue bars). (C) Smoothed low energy electron pitch angle distributions at 66.0° ahead, and 150.8° behind Enceladus.