Data Analysis

Spectra were bias-subtracted and flat-fielded in the standard manner, and intensity calibrated by comparison to the centers of Jupiter's and Saturn's disks observed on the same nights[25]. Earth's atmosphere blurred Enceladus' disk from 0.09" to 0.8" full-width half-maximum, but Enceladus stray light does not contaminate spectra more than two arcseconds away. We summed eight 30-minute exposures targeted at the dusk E-ring ansa. We separately summed five 30-minute observations targeted on Enceladus after correcting for their changing Doppler shifts and removing sky background including emissions by subtracting the average sky spectrum north of Enceladus from the entire frame.

Upper limits on sodium emission were derived by simulating features of different intensities with appropriate photon noise, adding them into the spectra at the proper Doppler shift for each observation, and evaluating which would clearly be identified as emissions. Emission surface brightness is expressed in Rayleighs, abbreviated R, with 1 R = $(10^6/4\pi)$ photons/(cm^2 steradian second). While our upper limits may seem conservative compared to the readily detectable 4R airglow line, this is because the airglow line (1) spans the entire slit, while our upper limit applies to smaller spatial regions; (2) lies on a uniform continuum background as opposed to the modelled emissions which lie within the strong spectral variations of the solar Fraunhofer line. Formal error analysis confirms that our visual approach is twice as conservative as 3-σ statistical errors. The observed brightness limits are linearly converted to maximum sodium column abundances in Table 1using Saturn's distance from the Sun and

Enceladus' Doppler shift relative to the minimum of the solar Fraunhofer line. Given the low column abundances, no correction for optical thickness is needed.

Numerical Modeling

The model tracks individual particles (atoms or molecules) as they leave Enceladus' south pole and expand away on escape trajectories. The model can simulate spectral line shapes and intensities for any Enceladus orbital longitude and spectrograph slit location, including the source region at Encledus. The southward ejection velocities of ~400 m/s estimated from Cassini data[15,16] exceeds Enceladus' escape speed of 240 m/s. Once particles have escaped, they orbit Saturn every ~33 hours and are bombarded by magnetospheric particles and sunlight. The dominant loss processes and their lifetimes are molecular photodissociation (~9 hrs)[26]; photoionization (~1500 hours[27]) and electron impact ionization[28] (~10^4 hours within $0.5R_s$ (Saturn radii) of Enceladus' orbit, but reduced in our model to little as 100 hours outside at 5 R_s, based on spatially-resolved Cassini data[29]). Collisions with Saturn's rings will occur for sodium atoms after about 700 hours (explained below), but collisions of Na molecules with E-ring particles, Enceladus, or other moons can be neglected.

The model can be run under different assumptions for the source of sodium. Sodium may be ejected in atomic form, as at Io and Europa, and appear in the plume near Enceladus. Alternatively, if sodium is ejected in particle or molecular form then sputtering and photodissociation will liberate it in atomic form and add a small random velocity component. The model assumes that after dissociation, the fragments gain ~1km/sec of random velocity (0.1eV) and are therefore dispersed from the original orbits[30]. Additional models examining different post-dissociation velocities confirmed that our detection limits are valid for velocities up to 3 km/sec, spanning the plausible range for plausible molecules[31].

Radiation pressure (caused by the same resonant scattering that makes sodium so visible) will significantly alter sodium atom orbits. On Saturn's dusk side, scattering occurs as the atom recedes from the sun, hence will accelerate it and raise the orbit on the opposite side of Saturn. There, each scattering slows the atom and lowers the orbit on the dusk side. Together these effects make orbits more elliptical and shift them towards Saturn's dawn side. This accelerates sodium loss in two ways: First, as apoapse moves outwards, sodium experiences a harsher ionizing electron environment, reducing the lifetime to 100-200 hrs[iv]. Second, as periapse moves inwards, atoms are eventually adsorbed onto Saturn's rings at 2.3Rs, placing an upper limit of ~20 orbits (~700 hours) on sodium atoms.

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