nature Vol 459 | 25 June 2009 | doi:10.1038/nature08070

LETTERS

No sodium in the vapour plumes of Enceladus

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The discovery of water vapour and ice particles erupting from Saturn's moon Enceladus fuelled speculation that an internal ocean was the source[1–3]. Alternatively, the source might be ice warmed, melted or crushed by tectonic motions[4]. Sodium chloride (that is, salt) is expected to be present in a long-lived ocean in contact with a rocky core. Here we report a ground-based spectroscopic search for atomic sodium near Enceladus that places an upper limit on the mixing ratio in the vapour plumes orders of magnitude below the expected ocean salinity[5]. The low sodium content of escaping vapour, together with the small fraction of salt-bearing particles[6], argues against a situation in which a near-surface geyser is fuelled by a salty ocean through cracks in the crust[1]. The lack of observable sodium in the vapour is consistent with a wide variety of alternative eruption sources, including a deep ocean[6], a freshwater reservoir, or ice. The existing data may be insufficient to distinguish between these hypotheses.

The discovery of icy particles containing ~1% sodium chloride in Saturn's E ring has led to the suggestion that they formed from a salty ocean below Enceladus' icy crust[6]. But the vast majority of escaping matter is gaseous—mass proportions for vapour:low-sodium particles:1%-sodium particles are[6] approximately 4,000:20:1. It is therefore essential to examine the bulk of material escaping Enceladus to test and further constrain the hypothesis. If sodium is present in atomic form in the vapour, it will be readily visible in the plume near Enceladus; if sodium is ejected in molecular form, it will photodissociate into atomic form and will orbit Saturn for weeks to months and again be readily observed. Escaping sodium is a surprisingly common phenomenon in the Solar System, being easily detected at Io[7], Europa[8], Mercury[9], the Moon[10] and comets[11], and sodium chloride vapour has been detected above Io's volcanoes[12]

Sodium is arguably the most easily detected atom among common Solar System elements. Its atomic structure places its allowed transitions near the peak of the solar spectrum, so even small amounts of sodium appear bright in resonant scattering of sunlight. We undertook a deep search for atomic sodium D-line emission (589.0, 589.6 nm) near Enceladus and Saturn's E ring using high-resolution long-slit spectroscopy. We used the 10-m Keck 1 telescope with the HIRES spectrograph[13] and the 3.9-m Anglo-Australian Telescope (AAT) with the UCLES spectrograph[14] (Table 1). The high resolution of echelle spectrographs disperses the solar continuum reflected by Enceladus, as well as the solar continuum from Saturn and its rings scattered by Earth's atmosphere and the telescope optics into the spectrograph slit. The long slit allows the determination of independent spectra from many locations along the slit that can be summed to increase signal-to-noise ratio or differenced for sky background subtraction.

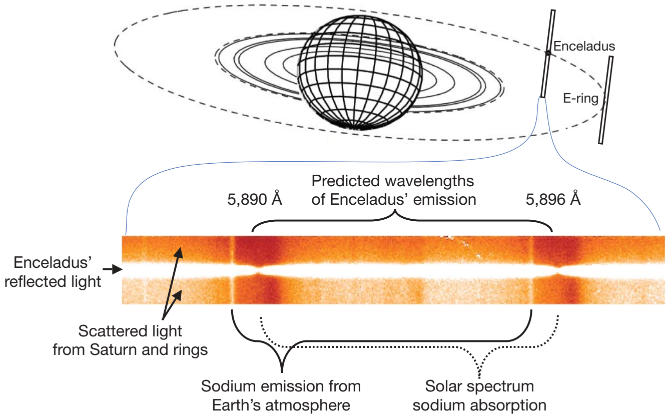

Figure 1 | Observing geometry and corresponding sodium D-line spectrum of Enceladus and nearby E ring. Bottom, 30-min spatially resolved spectrum obtained with the Keck 1 HIRES spectrograph on 25 February 2007 at 09:59 UT, with wavelength information displayed horizontally and spatial information displayed vertically. The Enceladus and scattered Saturn/ring spectra display the strong solar Fraunhofer D-line absorptions. Sodium features appear at different wavelengths due to their respective Doppler shifts; the predicted Doppler-shifted locations of emission from Enceladus sodium are indicated. Top, diagram showing geometry of Saturn, its E ring (outer dashed line), slit position for the spectrum shown, and also the observing geometry for dedicated E-ring observations. The spatial resolution of the Keck observations is 0.8″ full-width at half-maximum, corresponding to ~5,000 km or ~20 Enceladus radii.

Figure 1 shows the observing geometry and a typical Keck spectral image. Table 1 summarizes the brightness upper limits obtained from both telescopes and derived sodium abundances (Supplementary Information). The Keck observations place more restrictive upper limits owing to this telescope's larger aperture and lower scattered

Table 1 | Observations

Observatory/ instrument	Dates (UT)	Resolving power	Slit size (arcsec)	Exposure times (min)	No. of expo-sures	Upper limit near Enceladus		Upper limit near E ring	
						Brightness (R)	Column abundance (atoms cm^{-2})	Brightness (R)	Column abundance (atoms cm^{-2})
Keck 1/ HIRES	25 Feb. 2007	60,000	14 × 0.57	30	13	4–8	(0.5–1.0) × 10^8	2	2.5 × 10^7
AAT/ UCLES	27 Feb. –2 Mar. 2007	80,000	12 × 0.5	20	21			100	1.3 × 10^9

In the seventh and eighth columns are shown the upper limit of sodium D-line emission brightness, and the derived sodium column abundance. AAT, Anglo-Australian Telescope.

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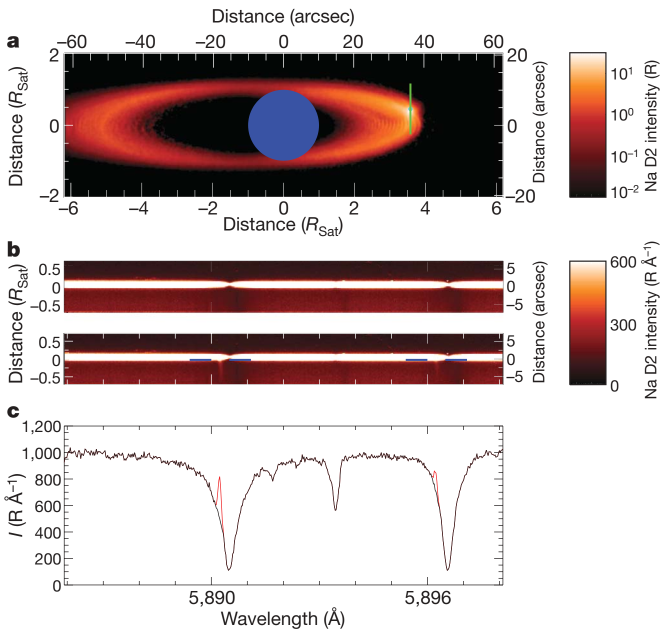

Figure 2 | Determining the 4 × 10^{-7} upper limit for direct sodium ejection into a south-directed plume. a, Plume model image for the geometry of Keck Enceladus observations. Intensity scaling is logarithmic. The model uses an atomic sodium escape rate of 0.4 g s^{-1}, corresponding to an Na/H_2O mixing ratio of 2×10^{-6}. The green line represents the slit across Enceladus. The asymmetry is caused by solar radiation pressure on atomic sodium. R_{Sat}, Saturn radius. **b**, Sum of all sky-subtracted spectral images for Enceladus observations with (bottom) and without (top) 40 R of simulated sodium plume emission. The simulated signal does not include photon noise. **c**, Spectra of the spatial region indicated by the blue lines in **b** located along the lower edge of Enceladus' continuum near the simulated emissions. The black curve is data alone, the red curve adds 40 R of simulated emission derived from the model in **a**. This simulated emission would be readily detectable; the actual upper limit derived from the original spectrum is 8 R, yielding Na/$H_2O < 4 \times 10^{-7}$. Further information on the derivation of the upper limits is given in the Supplementary Information. *I*, intensity.

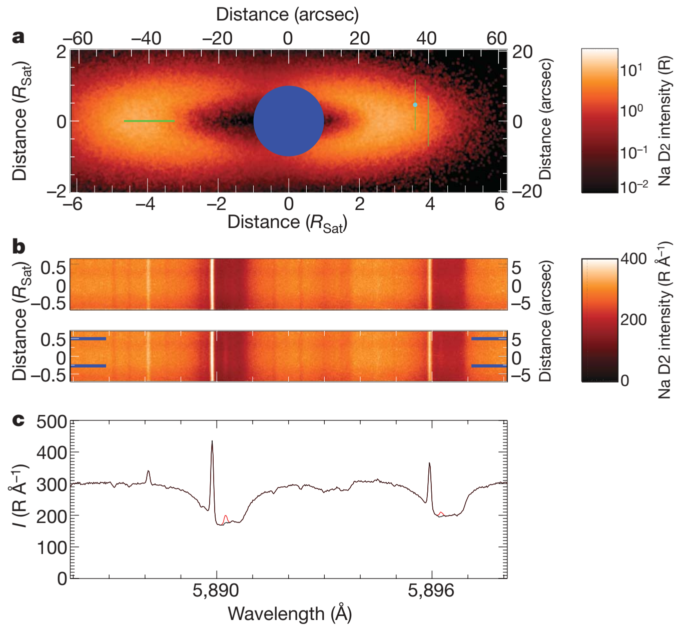

Figure 3 | Determining the 7 × 10^{-6} upper limit for a molecular source, with panels displaying the same information as in Fig. 2. a, Model image for sodium produced by molecular dissociation as described in the text. The model uses an atomic sodium escape rate of 2 g s^{-1}, corresponding to an Na/H_2O mixing ratio of 1×10^{-5}. The green lines represent, from left to right, the AAT east E-ring ansa slit, the Keck slit at Enceladus, and the Keck slit at the west E-ring ansa. (An ansa is the outer edge of a ring as projected on the sky.) The spatial distribution for sodium sputtered from E-ring particles is essentially the same. **b**, Sum of all spectral images for Keck E-ring observations, with and without 3 R of simulated emission. **c**, Spectra summed over the spatial region indicated in **b** by the horizontal blue lines at the left and right edges. The black curve shows data alone; the red curve adds 3 R of simulated E-ring sodium emission. The observed upper limit from these data is 2 R, yielding Na/$H_2O < 7 \times 10^{-6}$. Similar analysis of the Keck Enceladus slit positions yield Na/$H_2O < 1.4 \times 10^{-5}$, and the AAT observations find Na/$H_2O < 4 \times 10^{-4}$. The upper limit for molecular ejection is higher than for atomic ejection, as sodium is first dispersed in undetectable molecular form far from Enceladus into a ring around Saturn, then dispersed from that ring through dissociation, thereby filling a much larger volume. The Fraunhofer lines are broader than those in Fig. 2 owing to the roughly equal admixture of scattered light from Saturn and from the rings at different Doppler shifts.

light background. In summed Keck E-ring spectral images (Figs 2b, 3b) we find an upper limit of 2 Rayleighs (2 R) on D-line emission. In the Keck Enceladus spectral image (Fig. 2b), where stray light from the satellite increases the background, we place an upper limit of 4 R at distances ≥2″ from Enceladus and 8 R at 1″. Each spectral image contains three slit-filling night sky emissions of brightnesses 4 R, 32 R, 17 R from left to right. (The first line comes from OH and the other two from sodium; they appear at approximate brightnesses and relative strengths consistent with past observations[15].) The ease of detecting the 4 R airglow line confirms we can confidently rule out emissions of this magnitude from Enceladus, the E ring or even a cloud larger than the slit length. For reference, the observed sodium brightnesses near Io and Europa are 200 kR and 10 kR; sodium emission from Io was detectable on these nights within seconds but could not be detected at Enceladus in more than six hours.

We convert the limiting column abundance into an upper limit on the plume sodium content by ratioing a modelled upper limit on sodium escape to the 150 kg s^{-1} of H_2O escape[16–18]. Our Monte Carlo model includes all major source, loss and transport processes for atomic sodium, and has been used to study neutral clouds at Io[19], Europa[20] and Enceladus[21] (Supplementary Information).

Figures 2 and 3 also show model results for sodium ejection in atomic or molecular form. With atomic ejection, sodium is visible immediately on ejection. Sodium eventually forms a complete torus around Saturn, but the high concentration in the plume near Enceladus dominates the brightness. The 8 R upper limit at the plume position near Enceladus translates to a very stringent upper limit of Na/$H_2O < 4 \times 10^{-7}$. Sodium escaping in molecular form (Fig. 3) does not become visible until photodissociation after forming a narrow molecular torus around Saturn. Keck E-ring slit pointings constrain Na/$H_2O < 7 \times 10^{-6}$, and the AAT data independently constrain Na/$H_2O < 4 \times 10^{-4}$. Sodium supplied by E-ring particle sputtering will resemble Fig. 3. The sodium mixing ratio of these particles[6] (referenced to the observed H_2O escape) is $\sim 5 \times 10^{-7}$, so our Keck upper limits are consistent with the detection reported in the companion paper[6].

Our observations show that the bulk of mass escaping Enceladus has much lower salt content than ocean models. Our upper limit for atomic escape, Na/$H_2O < 4 \times 10^{-7}$, is 5,000 times smaller than the mixing ratio (2×10^{-3}) of the sodium-rich ocean model[5], and our molecular upper limit, Na/$H_2O < 7 \times 10^{-6}$, is still 30 times lower than the 2×10^{-4} sodium-poor ocean model[5]. In fact, the lack of detectable sodium makes Enceladus unusual among objects with thin atmospheres and measurable atmospheric escape, namely Io, Europa, the Moon and Mercury.

The observed low sodium content in the vapour leads to five conclusions about plausible plume sources. First, the vapour could clearly result from evaporation from a low-salinity liquid reservoir, from warm ice sublimation, or from clathrate decomposition[22], though these mechanisms currently do not address the observed salt-bearing particles[6]. Second, the escaping gas cannot come from complete vaporization of ocean water including its dissolved salts, as might occur from a near-surface geyser boiling into a vacuum[1]. Third, vapour low in sodium can originate from a deep salty ocean, but only if evaporation occurs in equilibrium at the interface of a large liquid/vapour reservoir, as detailed in the companion paper[6] and in ref. 23. Fourth, similar scenarios in which ocean water flows nearer the surface along narrow cracks may prove unworkable. In the confined vent plumbing, preferential evaporation of the more volatile H_2O could enrich salt content in the liquid, possibly choking off the vent or leading to the ejection of very high salinity particles, which are not observed[6]. Fifth, a hybrid scenario, in which a low-salinity reservoir becomes enriched in the vent plumbing, could explain both the low-sodium vapour and the observed salt-bearing particles. In this scenario, however, the low values of salinity would indicate little exposure to the rocky core. We conclude that the observed sodium content of particles and vapour argue against certain plume eruption models and constrain others, but are insufficient to distinguish between these remaining scenarios. It remains plausible that more than one mechanism is at work; models based on evaporation of water require a separate mechanism such as clathrate decomposition to explain other escaping gases observed by Cassini's INMS instrument[24].

Received 24 October 2008; accepted 8 April 2009.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements Some of the data presented here were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the financial support of the W.M. Keck Foundation. We also acknowledge the Anglo-Australian Telescope and its staff. This work was supported by the National Science Foundation's Planetary Astronomy Program and the NASA Postdoctoral Program. This paper has benefited from discussions with M. Zolotov, J. Spencer, C. Porco, T. Johnson, A. Ingersoll, W. McKinnon, C. Mackay, F. Postberg, J. Schmidt, S. Kempf and R. Pappalardo.

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