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Negative ions in the Enceladus plume

A.J. Coates[a,b,*], G.H. Jones[a,b], G.R. Lewis[a,b], A. Wellbrock[a,b], D.T. Young[c], F.J. Crary[c], R.E. Johnson[d], T.A. Cassidy[d], T.W. Hill[e]

[a] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking RH5 6NT, UK
[b] Centre for Planetary Sciences at UCL/Birkbeck, Gower St., London WC1E 6BT, UK
[c] Southwest Research Institute, Division of Space Science and Engineering, 6220 Culebra Road, San Antonio, TX 78227-1301, USA
[d] University of Virginia, Engineering Physics, Thornton Hall, Charlottesville, VA 22904, USA
[e] Physics and Astronomy Department, Rice University, MS 108, Houston, TX 77251-1892, USA

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ABSTRACT

During Cassini's Enceladus encounter on 12th March 2008, the Cassini Electron Spectrometer, part of the CAPS instrument, detected fluxes of negative ions in the plumes from Enceladus. It is thought that these ions include negatively charged water group cluster ions associated with the plume and forming part of the 'plume ionosphere'. In this paper we present our observations, argue that these are negative ions, and present preliminary mass identifications. We also suggest mechanisms for production and loss of the ions as constrained by the observations. Due to their short lifetime, we suggest that the ions are produced in or near the water vapour plume, or from the extended source of ice grains in the plume. We suggest that Enceladus now joins the Earth, Comet Halley and Titan as locations in the Solar System where negative ions have been directly observed although the ions observed in each case have distinctly different characteristics.

1. Introduction

One of the key results from the Cassini mission was the discovery of the atmospheric plume of Enceladus, from observations of a distortion of the magnetic field which was inferred to be due to ion pickup (Dougherty et al., 2006). The plume structure extending above Enceladus' South pole, was found to be multiple by Hansen et al. (2006), who also inferred an outflow rate of neutral water of >150 kg s^{-1}. The plume composition was further studied by Waite et al. (2006) who found that the plume structure extended to 4000 km from Enceladus. They also found that water dominated the composition, and that additional species included CO_2, CO or N_2, and CH_4 and traces of higher masses. Further investigation of the plasma environment showed direct evidence for a flow deflection from the Cassini Plasma Spectrometer (CAPS) and an inferred rate for ion production from charge exchange and ion pickup at a rate of 100 kg s^{-1} (Tokar et al., 2006). Modelling by Burger et al. (2007) indicated that the plume structure observed by INMS and UVIS was consistent with a weak global source and a much stronger source near the South pole (~2–3 kg s^{-1}). This source is consistent with the mass loading rate inferred from the magnetic field, but suggests that an additional, perhaps extended, source is required to explain the CAPS ion deflection measurements.

Another key new result from Cassini at Titan was the detection of negative ions at high altitudes (950–1175 km) in Titan's ionosphere. Evidence for these was presented by Coates et al. (2007), and compared with positive ions and with neutrals by Waite et al. (2007, 2008, 2009); see review by Coates (2009). At Titan, the heavy negative ions we observe may be the precursors of sub-micron and micron sized particles. It has been suggested such ions might coalesce into tholins high in the atmosphere (e.g. Sagan et al., 1993), eventually precipitating on the surface. Chemical models are now being developed to include these light (Vuitton et al., 2009) and heavy (Waite et al., 2008) negative ions.

The negative ions were detected by the Electron Spectrometer (Linder et al., 1998), one of three sensors making up the Cassini Plasma Spectrometer (CAPS, Young et al., 2004). They were observed in the spacecraft ram direction, i.e. the direction of travel of the spacecraft, during Cassini's lowest altitude Titan encounters. The spacecraft motion through the cold ionosphere revealed the ions in the ram direction as a set of peaks in energy per charge, and hence in mass per charge. The CAPS actuator is designed to increase the angular acceptance of the instrument by moving the field of view.

Apart from the observations at Titan, negative ions have also been detected in Earth's D-region (e.g., Hargreaves, 1992). They can coexist with electrons at D-region altitudes where they form

* Corresponding author. Address: Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking RH5 6NT, UK.
E-mail address: ajc@mssl.ucl.ac.uk (A.J. Coates).

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primarily by electron attachment to electronegative species such as O. They were also seen as negative molecular ions at Comet Halley in the inner coma region, again coexisting with electrons (Chaizy et al., 1991).

During Cassini's E3 flyby of Enceladus on 12th March 2008, a similar and unexpected signature was seen. In this paper we present the evidence for, and an initial interpretation of, this population of negative ions.

2. Enceladus encounter, 12th March 2008

Fig. 1 shows a schematic illustration of the Cassini trajectory through the Enceladus plumes. During E3 the spacecraft flew at 14.4 km/s in a North–South direction through the plumes following closest approach (CA). The CAPS actuator was kept fixed during this encounter in order to sample the spacecraft ram direction at high time resolution; the ram direction was between anodes 4 and 5.

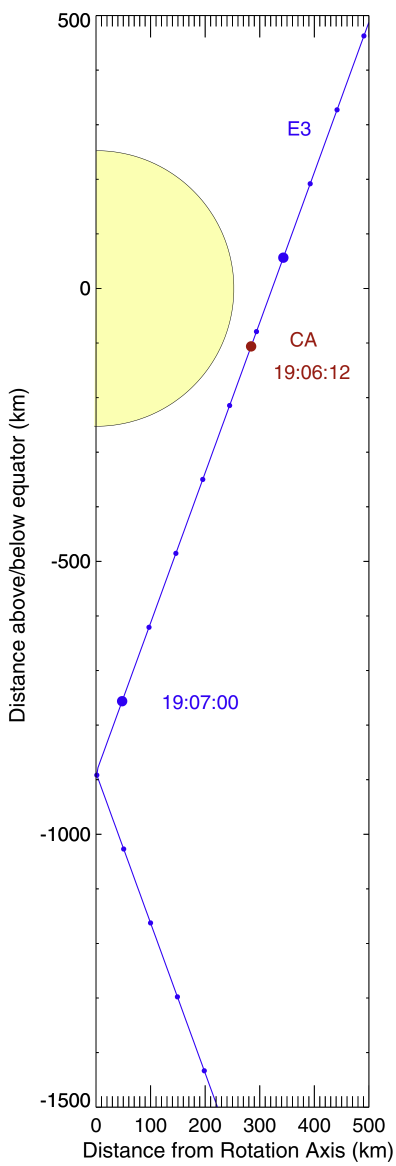

Fig. 1. Illustration of the E3 encounter trajectory through the plume. Tick marks are 10 s apart; CA denotes the time of closest approach, times given are in UT on 12th March 2008.

An overview of the CAPS-ELS data below 2 keV from anodes 4, 5 and 6, during the E3 encounter is shown in Fig. 2. Anode 5 views closest to the ram direction. The colour scale on the figure is counts per second. The spacecraft enters the Enceladus plume soon after CA (c.f. Fig. 1).

The low energy magnetospheric plasma has energy <10–20 eV. Before and after the Enceladus encounter, the density of these electrons (not shown) is consistent with the density from RPWS observations of ~70–80 cm^{-3} (Farrell et al., 2009), assuming a spacecraft potential of -2 V in the ELS data analysis.

In Fig. 2, a penetrating radiation background is observed across all energies (seen in the >10 eV region) at the beginning of the plot. This is due to ~2 MeV electrons penetrating to the detector. This background reduces in intensity towards the right hand side of the plot, probably a result of the energetic particle 'shadow' behind Enceladus (Jones et al., 2006).

The intense, higher energy per charge population observed by ELS (>~500 eV/q) is found to be associated with charged ice grains in the plume itself (Jones et al., 2009) and is not discussed further here. We focus on the peaks in count rate observed at intermediate energies (~10–1000 eV; see Figs. 2 and 3).

These peaks are observed to maximise sharply in the ram direction (anode 5, see Fig. 2), consistent with the idea that ELS is sampling a cold population of negative ions – perhaps part of a 'plume ionosphere' at Enceladus. Indeed, this population has similar properties to that seen at Titan (Coates et al., 2007). At Titan and Enceladus, we identify this population as negative ions for the following reasons: the particles are negative due to the voltages on the electrostatic analyser; sharp peaks are consistent with the spacecraft ramming through a cold ionospheric population, and as seen by ELS the ions are supersonic and therefore narrow; the sharp peaks, in energy and in (ram) angle, indicate negative ions rather than electrons, because although the ambient electrons are "cold" they are highly subsonic (higher thermal speed than the ram velocity) and therefore much more isotropic (e.g., Coates et al., 2007). Also, if the populations were electrons they would be highly non-gyrotropic at each energy level and time where they are seen. This is impossible because the magnetic field would need to be in the ram direction at all times during each of the negative ion observations, which is not observed (Dougherty et al., 2006 and Dougherty et al., private communication, 2008).

Fig. 3 shows an individual energy spectrum from the ELS at 19:06:47 UT, with the location of the negative ion peaks indicated. These peaks are highly reminiscent of the negative ion peaks observed by ELS at Titan, except that the flyby speed is higher here and, if the peaks are due to negative ions, the conversion factor from energy/charge to mass/charge is $m_{amu} = 0.924 E_{eV}$ for the 14.4 km/s flyby speed. If our interpretation is correct, we are detecting negative ions between ~16 and 500 amu/q.

In Fig. 4 we present further individual spectra from the plume region. Clearly there is a significant variation of the peak intensities with time (also visible in the spectrograms, Figs. 2 and 3). In each spectrum, the peaks are superimposed on a background that peaks at ~5 eV and that we assume to be due to electrons since they are isotropic or nearly so, which is consistent with a highly subsonic thermal electron population. These spectra are measured during a 10 s interval within the plume (see Fig. 1), and the variability in the spectra, which is also visible in Fig. 2, is a combination of spatial effects within the overall plume structure (which are likely to dominate) with temporal variation, though we cannot unambiguously distinguish the two.

Adapting the method of Coates et al., 2007, we interpret the count rate at each energy as due to a flux of cold, negative ions (plus background) arriving from the spacecraft ram direction. We identify mass 'groups' associated with the peaks in the energy spectra. With this assumption the groups fall in the mass ranges

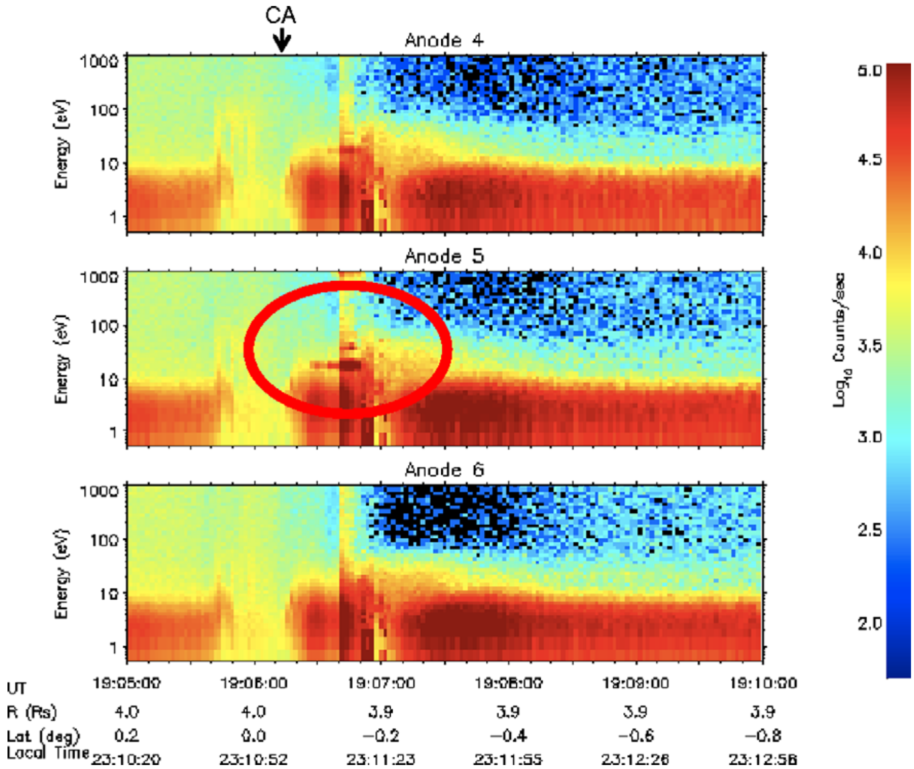

Fig. 2. CAPS-ELS data from anodes 4, 5 and 6 during the E3 encounter illustrate that the peaks are observed in the ram direction. The arrow marked CA indicates the time of the closest approach of Cassini to Enceladus (CA, 19:06:12 UT).

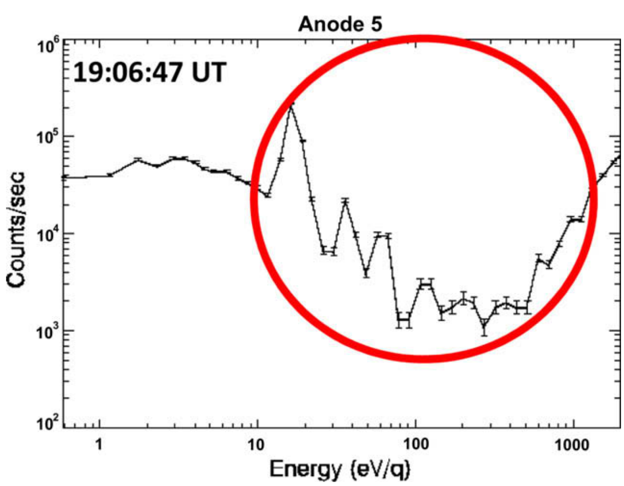

Fig. 3. CAPS-ELS energy spectrum from anode 5 with the negative ion peaks indicated.

9–27, 27–45, 45–70, 70–300 and 300–500 amu/q. We have calculated the density assuming negative ions with the results shown in Fig. 5. Clearly there is a higher density of negative ions at low masses, and again there are significant changes in the relative abundances with position along the spacecraft track.

In Fig. 6 we compare INMS neutral data (top panel courtesy INMS team, NASA/JPL/SwRI with the peaks observed by CAPS-ELS. The first ELS peak overlaps with the water-associated peak in INMS, and there is a strong suggestion that the first and second ELS peaks correspond to the water group ion mass and double this mass, respectively. The third ELS peak may include multiples 3 and 4, as well as possible additional ions. The heavier peaks (up to ~500 amu or more), seen in Figs. 2 and 4, may also be associated with more complex ions, either higher multiples of mass 16–18 (with the low multiples observed up to mass ~72), or perhaps different, more complex species.

3. Discussion

Here we find that negative ions are present in the plume of Enceladus Water-associated negative ions (e.g. OH^-, O^-, H^-) can be produced from neutral H_2O in the plume of Enceladus, by dissociative electron attachment. The observations show that these ions are short-lived due to photodetachment. Huebner et al. (1992) found that the reaction $H^- + \nu \rightarrow H + e^-$ occurs at a rate of 14 s^{-1} at Earth, corresponding to a rate of 0.17 s^{-1}, or a 6 s lifetime at Saturn. The other relatively small ions shown are expected to be short-lived also (Huebner et al., 1992).

As discussed above, the mass peaks up to at least ~72 amu (corresponding to ~80 eV) may be associated with negatively charged water group clusters. While positive water ion clusters were expected to be present near Enceladus due to low-energy ion–molecule reactions (Johnson et al., 1989), negative ion clusters were not predicted.

Larger clusters may also form, and may contribute to the higher energy observations, but other effects may dominate as discussed by Jones et al., 2006. The 'valley' in the energy spectrum (~2–300 eV) is interesting. Since there is no such valley in the negative ion energy distributions at Titan (Coates et al., 2007), its presence might be support for a different process at work and dominating at the higher energies. However, it might also be the product of a declining density of neutral clusters with increasing mass times increasing electron attachment energy, so that detachment requires photons at shorter wave lengths. Although this emphasises that the formation process differs from that at Titan, the negative ion densities do decrease with increasing mass as shown in Fig. 5.

The identity of some of the higher mass peaks (up to ~500 amu) may also be consistent with further multiples of the water group

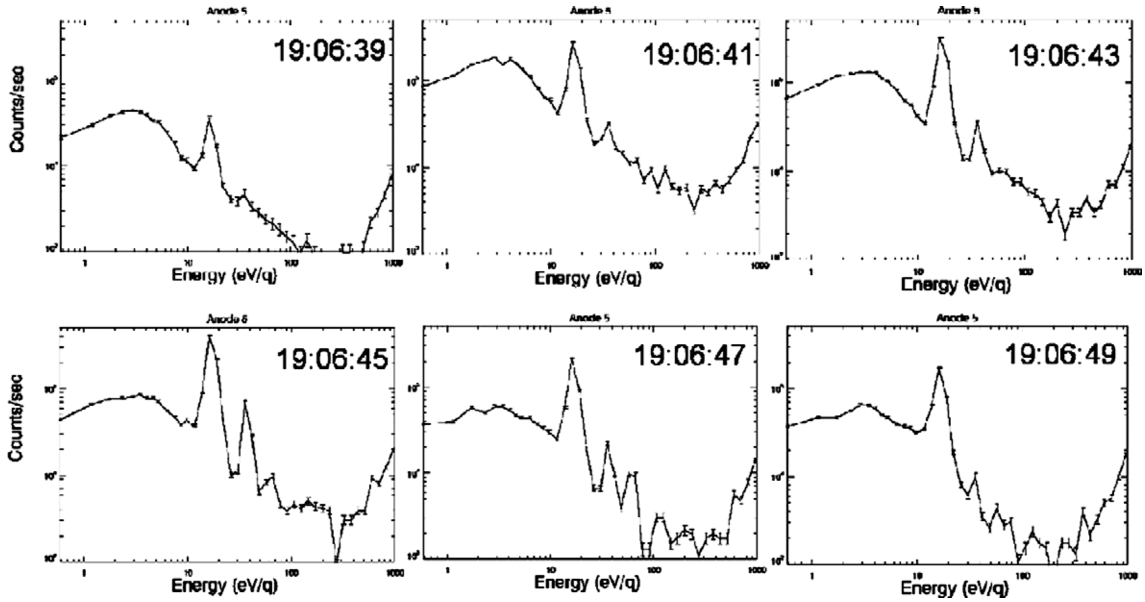

Fig. 4. CAPS-ELS energy spectra from the plume region.

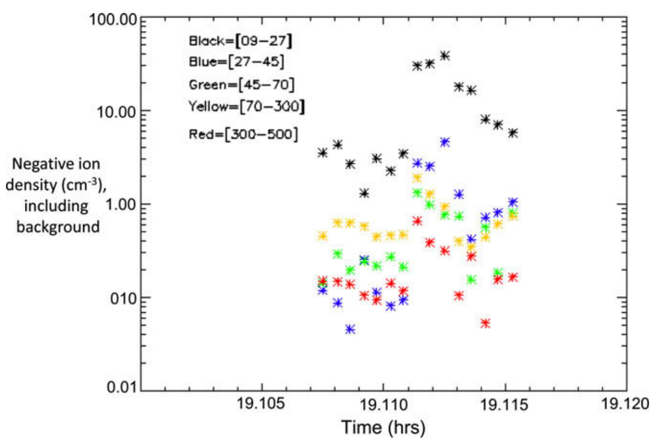

Fig. 5. Density of negative ions (including background) as a function of mass group in the plumes of Enceladus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

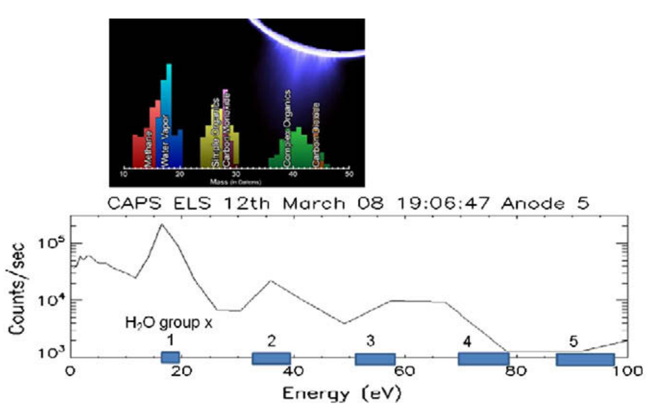

Fig. 6. Comparison of ELS peaks with the neutral mass peaks observed by INMS (latter courtesy INMS team, NASA/JPL/SwRI). Integral multiples of the H_2O group mass (16–18 amu) are shown for comparison. The energy–mass conversion for negative ions in ELS is $m_{amu} = 0.924E_{eV}$ (see text).

masses 16–18. However, more complex carbon-based molecules, such as those seen by INMS (Waite et al., 2009) might enhance the likelihood of the presence of very large clusters which also have higher attachment energies.

Note that, at the time of their peak density, the negative ions up to ∼500 amu account for about 50% of the number density of ambient electrons. There are some indications from RPWS data that the electron density is lower during the plume passage which would compensate (Farrell et al., 2009). At this time, however, the total density of negatively charged particles is dominated by the higher energy component (Jones et al., 2009).

4. Summary and conclusions

Summary of observations:

- CAPS-ELS observations from Enceladus show well defined energy peaks in the plume.
- The intensity of the peaks maximises in the ram direction, behaviour reminiscent of negative ion peaks at Titan.
- The conversion from energy to mass is close $m_{amu} = 0.924E_{eV}$ for this flyby speed.
- Assuming negative ions, the mass groups are 9–27, 27–45, 45–70, 70–300 and 300–500 amu/q.
- The negative ions may be part of a ‘plume ionosphere’.
- The low mass negative ions appear to be water ‘cluster ions’, multiples of mass 16–18 amu, while higher mass ions up to 500 amu/q may be water cluster ions or may be other, more complex species. Above this energy the bulk of the signal is due to other effects (Jones et al., 2009).

The process by which negative ions are formed is assumed to be electron attachment. The presence of the negative water group ions is additional evidence for water emission from Enceladus, and the short lifetime for the small negative ions shows that they are created in or very near the plume from expelled water vapour originating from Enceladus itself, or from the extended source provided by the expelled ice grains.

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