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# Analysis of a sequence of energetic ion and magnetic field events upstream from the Saturnian magnetosphere

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ABSTRACT

The existence of energetic particle events to ~200 $R_S$ upstream and ~1300 $R_S$ downstream of Saturn was established during the Voyager 1, 2 flybys in 1980 and 1981, respectively. The origin of the events could not be determined with certainty because of lack of particle charge state and species measurements at lower ( $<300$ keV) energies, which dominate the spectra. High sensitivity observations of energetic ion directional intensities, energy spectra, and ion composition were obtained by the Ion and Neutral Camera (INCA) of the Magnetospheric IMaging Instrument (MIMI) complement, with a geometry factor of ~2.5 $cm^2$ sr and some capability of separating light (H, He) and heavier (C, N, O) ion groups (henceforth referred to as 'hydrogen' and 'oxygen', respectively). Charge state information was provided where possible by the Charge-Energy-Mass Spectrometer (CHEMS) over the range ~3–235 keV per charge, and magnetic field (IMF) data by the MAG instrument on Cassini. The observations revealed the presence of distinct upstream bursts of energetic hydrogen and oxygen ions whenever the IMF connected the spacecraft to the planetary bow shock to distances $>80$ $R_S$. The events exhibited the following characteristics: (1) hydrogen ion bursts are observed in the energy range 3–220 keV (and occasionally to $E>220$ keV) and oxygen ion bursts in the energy range 32 to ~700 keV. (2) Pitch angle distributions are initially anisotropic with ions moving away from the bow shock along the IMF, but tend to isotropize as the event progresses in time. (3) The duration of the ion bursts is several minutes up to 4 h. (4) The event examined in this study contains significant fluxes of singly charged oxygen. (5) Ion bursts are accompanied by distinct diamagnetic field depressions with $\beta>10$, and exhibit wave structures consistent with ion cyclotron waves for $O^+$ and $O^{++}$. Given the magnetic field configuration during the detection of the events and that energetic ions trapped within the magnetosphere of Saturn are $H^+$, $H_2^+$ and various water products including $O^+$, $O^{++}$, we conclude that O-rich upstream events must be particles leaking from Saturn's magnetosphere under favorable IMF conditions. The spectral evolution of the upstream events and their anisotropy characteristics are discussed in the context of current models.



## 1. Introduction

Ions have been observed upstream of Earth's bow shock as early as 1968 (Asbridge et al., 1968) to energies of a few keV, with later observations showing that such events extend to several tens to hundreds of keV (Lin et al., 1974; Sarris et al., 1976). It is now known that upstream ion events are ubiquitous upstream of planetary bow shocks such as those of Jupiter, Saturn, Uranus and Neptune, as demonstrated by the flybys of the Voyager spacecraft past the outer planets (Krimigis, 1992). It has been suggested that the origin of such energetic ion events is either local acceleration upstream of the planetary bow shock due to a Fermi-type process (e.g Lee, 1982) or leakage of pre-accelerated ions from the parent magnetosphere due to dynamical events such as substorms (Krimigis et al., 1978).

Each of the competing models had specific predictions such as the shape of the ion spectrum, including a cut-off at energies of order of ~150 keV in the case of Earth (Ipavich et al., 1981a), and a

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solar wind-like composition (Ipavich et al., 1981b). By contrast, the same events were interpreted as originating from inside the magnetosphere (e.g. Anagnostopoulos et al., 1986). These interpretations were based on multi-spacecraft observations inside and outside the magnetosphere that showed detailed time association between dynamical events in the magnetosphere itself and the upstream region. It had been difficult, however, to establish uniquely the origin of the energetic ions without detailed composition measurements, which became available in the mid-80s and early 90s. Such events (Krimigis et al., 1986) showed that singly charged oxygen ions were seen in the outer magnetosphere of Earth and simultaneously in the interplanetary medium (Möbius et al., 1986) and seemingly favored the magnetospheric origin of these upstream ions (Posner et al., 2002; Posner et al., 2003). Later studies, with measurements of abundance ratios but not charge state, were more suggestive of an interplanetary-source population as the likely source of these upstream events (Desai et al., 2006).

The magnetospheres of the outer planets were less ambiguous in the sense that they contained tracer ions that could be used to ascertain the source of upstream events. For example, particle events upstream of Jupiter seen by Voyager 1 and 2 contained abundant oxygen and sulfur ions that were only abundant inside the magnetosphere and rare in the upstream solar wind (Zwickl et al., 1981; Krimigis et al., 1985). Similarly, in the case of Uranus the spectral shape as well as the anisotropies demonstrated clearly that the origin of these ions was most likely the magnetosphere. In that case, however, there were not unique compositional or charge state signatures to prove absolutely that the magnetosphere was the only source for the upstream population (Krimigis et al., 1988). Finally, no upstream events were seen at Neptune, apparently because the IMF never connected the bow shock to the Voyager 2 trajectory.

The case of Saturn was an interesting and more complicated one; the existence of upstream events was shown by the two Voyagers to at least to 200 $R_S$ upstream (Krimigis et al., 1983) and approximately 1300 $R_S$ downstream (Behannon et al., 1985). Nevertheless, the origin was somewhat uncertain because of the inability to measure tracer ions (similar to $O^+$ at Earth and $O^+$ and $S^+$ at Jupiter) at lower, $<$200 keV energies to discriminate between solar wind and magnetospheric sources. As will be shown later, the Magnetospheric IMaging Instrument (MIMI, Krimigis et al., 2004), is able to make definitive measurements on both composition and charge state, as well as a comprehensive set of measurements of pitch angle distributions so that it is possible to address a number of issues associated with upstream events at Saturn. Unfortunately, there was not concurrent information on solar wind parameters, but the IMF measurements were sufficient to determine connection geometry to the planetary bow shock.

We find that there is a number of upstream events in the Saturnian environment with characteristics similar to those seen at other planetary bow shocks; these also exhibit power-law energy spectra, at least for protons, and contain unique traces of species such as $O^+$ and $O^{++}$, that are resident inside the magnetosphere of the planet. Further, the upstream ions energetically suppress the interplanetary magnetic field (IMF), producing evident diamagnetic signatures accompanied by ion cyclotron waves that can be identified in the magnetic field spectra. We suggest that such ions are leaking from the planetary magnetosphere and propagate upstream from the planet to the location of the Cassini spacecraft.

## 2. Instrument and data analysis

The MIMI instrument comprises 3 sensors that measure particles in specific energy ranges (1) the Ion and Neutral Camera (INCA) which measures ions and neutral species (~3 to ~200 keV/nuc); (2) the Charge-Energy-Mass Spectrometer (CHEMS) that measures ions and their charge states (~3–230 keV/e); and (3) the Low Energy Magnetospheric Measurement System (LEMMS), that measures ions (~0.02 to ~18 MeV) and electrons (0.015 to ~1 MeV). Principal use in this study is made of the INCA sensor, which with its large geometric factor of approximately 2.5 $cm^2$sr possesses high sensitivity to detect even the lowest intensity events in the upstream medium; and of CHEMS that can make precise measurements of composition and charge state, albeit at much lower sensitivity than that of INCA. The LEMMS sensor is used to examine the presence/absence of electrons and to expand the pitch angle coverage available through INCA. The magnetometer (MAG) investigation, (Dougherty et al., 2004) consists of a vector fluxgate sensor (VFG) and a helium sensor; we use the measurements obtained with the VFG that is most appropriate for the study we wish to conduct. Data sampling from the various sensors start with resolution of less than 4 s, and are appropriately averaged for the purposes of this study. Charge state measurements require accumulation of data over long periods of time to obtain significant statistics, as will be explained in the text.

The Cassini spacecraft is three-axis oriented for most of the time; therefore it points in specific directions as the sequence schedule dictates, but occasionally it rotates about the $z$-axis as the data are down-linked to Earth through the parabolic antenna. For the observations described in this work the spacecraft was three-axis oriented and viewed specific directions in space, as will be explained during the presentation. It is noted that the INCA field of view is 90° by 120° and, as an imaging sensor obtains an image in resolution as high as 64 by 64 pixels in both the ion or neutrals mode, as the case may be. It is therefore possible to obtain substantial angular distribution measurements even though the spacecraft may be pointed in a specific direction. Similarly, the LEMMS sensor is placed on a rotating platform and sampled a full 360° in each rotation of 86 s.

## 3. Upstream events during approach to Saturn

Fig. 1 shows the Cassini spacecraft trajectory during its initial approach to Saturn in June–July, 2004. The spacecraft Saturn Orbit Insertion (SOI) took place on day 183 and it was sent to a long-period outbound trajectory shown here up to day 220. Several upstream events were observed both through the inbound as well as outbound leg on the initial orbit but only the events shown during the inbound leg of the trajectory will be described in this paper. This specific period to be studied is shown in detail in Fig. 2; the top panel displays the intensity of energetic ions in the indicated energy intervals ranging from ~3 to $\geqslant$200 keV in total energy. These ions are primarily protons, although a small fraction (~5%) of helium ions contributes to this set of INCA channels. There is a general background of energetic ions throughout this period extending from day 175 through the end of day 179, when the spacecraft began to encounter the planetary bow shock several times, two of which occurred on that day, as indicated by magnetic field data in the lower panel of the figure. The most prominent upstream events occurred on day 176, although short-duration (approximately a few tens of minutes) events occurred on day 177 as well as on 178. Additional events seem to be present at the beginning of day 179 before the first bow shock encounter. We will concentrate our attention to the first group of events on day 176.

The upstream events are superposed on a slow overall increase in intensity above pre-event background as the spacecraft is approaching the bow shock. The events extend in energy to at