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CHARGE EXCHANGE IONS PRODUCED BY AN ION PROPULSION SYSTEM

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Abstract

In this paper, we present observations of charge exchange ions generated by the ion propulsion system (IPS) on the Deep Space One (DS1) spacecraft . We show that the equilibrium flux of charge exchange ions correlates well with IPS thrust levels, but that the flux requires approximately 4 hours to build up to equilibrium value after the start of IPS operation. In time of flight mass spectra, these ions appear as a broad peak which is consistent with a mixture of singly charged xenon and molybdenum and doubly charged xenon. We can not directly distinguish between these species, since the instrument was not operating at its designed high voltage levels during 1999. The instrument will operate at higher voltages during 2001, which should allow us to determine the composition of these ions. In addition, the data clearly show the presence of N^+ at times when ion propulsion system and the spacecraft's hydrazine reaction control thrusters both in use.

Introduction

The Deep Space One (DS1) spacecraft was launched in October, 1998, to validate 12 advanced technologies for use on future missions. These include the first use of solar electric ion propulsion system for primary propulsion, and a low-resource plasma spectrometer and time of flight mass spectrometer, the Plasma Experiment for Planetary Exploration (PEPE). During 1999, 899 hours of PEPE data were obtained while the ion propulsion system was operating.

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Description of Spacecraft and Instrument

The Deep Space One spacecraft's structure is based on the Miniature Seeker Technology Integration spacecraft built by Spectrum Astro for the Ballistic Missile Defense Organization. As shown in figure 1, the ion propulsion system is mounted on the –Z side of the spacecraft and the ion beam is directed in the –Z direction. Solar arrays extend in the +Y and –Y directions. The present paper focuses on results from the Plasma Experiment for Planetary Exploration (PEPE), mounted on the +Z/+X corner of the spacecraft. There is no direct line of sight between PEPE and the ion propulsion system

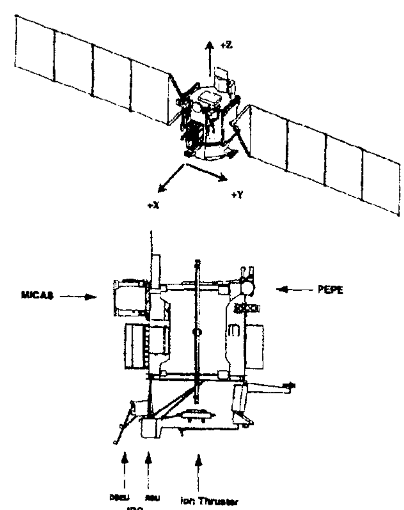

Figure 1: The Deep Space One spacecraft with locations of the PEPE, MICAS and IDS instruments, and the ion propulsion system.

. A set of plasma instrument, the IPS Diagnostic System (IDS), is located near the IPS on the –Z end of the spacecraft.

Deep Space One Ion Propulsion System

The 30-cm diameter, xenon ion propulsion system on Deep Space One by the NSTAR program, a collaboration between NASA Glenn Research Center, the Jet Propulsion Laboratory, Hughes Electron Dynamics and Spectrum Astro, Inc. Xenon is ionized and accelerated through an electric potential of up to 1.1 kV, applied across a molybdenum grid. The resulting ion beam generates a maximum thrust of 92 mN at a specific impulse of 3100s.[1] The accelerating voltage, thrust and current may be throttled, operating between 0.6 and 2.5 kW, with a peak efficiency around 2.3 kW. During 1999, the IPS was typically operated at a thrust level between 20 and 50 mN.

Some fraction of the xenon exits the thruster un-ionized, and may experience charge exchange reactions with the Xe^+ beam. In addition, molybdenum sputtered off the accelerating grids may also charge exchange. The result is a population of low energy ions. Depending on the details of the spacecraft potential and the Xe^+ beam, these charge exchange ions may impact the spacecraft, even at locations which do not have a direct line of sight to the source.[2] The contamination experiment on Deep Space One measured an accumulation of 2.6 nm/khr of molybdenum on a target without a direct line of sight to the IPS, probably due to the indirect trajectories of charge exchange ions[3]

PEPE Instrument Description

The Plasma Experiment for Planetary Exploration (PEPE) measures the flux of ions and electrons as a function of energy and angle with a "top hat" electrostatic analyzer (ESA), and ion composition using a time of flight mass spectrometer.[4] This 5.5 kg instrument is roughly similar in capabilities to the much larger (23 kg) CAPS instrument on the Cassini spacecraft.

Figure 2 shows a cutaway diagram of the instrument, which is cylindrically symmetric about the long axis. Ions and electrons enter the instrument through the deflection/collimation section. On entering, the particles are deflected by a pair of electrodes, so that only particles from a 11.25° range of angles are transmitted farther into the instrument. This angle is controlled by stepping the voltage across the deflector electrodes, allowing PEPE to view particles from elevation angles of ±45° in 16 steps. The "blind" region is

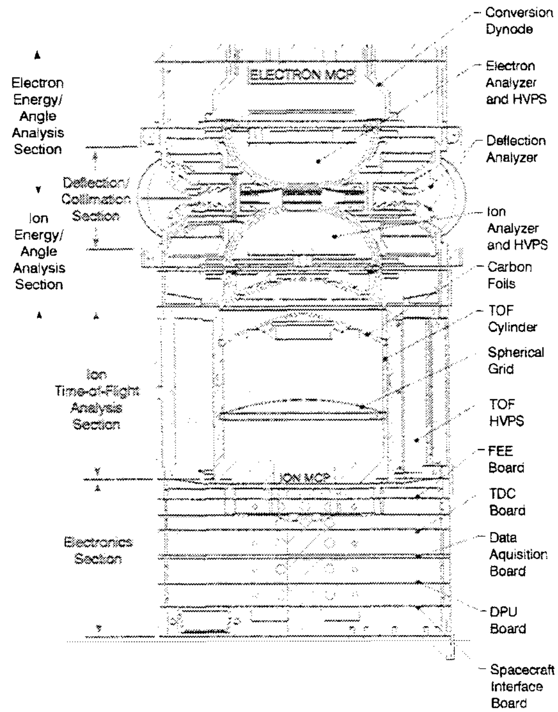

Figure 2: Cutaway diagram of the PEPE instrument

oriented along the spacecraft's Y axis. Once filtered for elevation angle, the particles pass through curved plate electrostatic analyzers.

Positive and negative voltages are applied to the inner surfaces of two sets of toroid electrodes, while the outer surfaces are held at ground. This creates an electric field which deflects electrons in one direction (upward in figure 2) and ions in another. Particles with an appropriate energy per charge are transmitted through the gap between the toroidal electrodes. Particles with too great or too low an energy hit the outer or inner electrode. This ESA transmits electrons with an energy range of 8.5% and ions in a 4.6% energy range. By stepping the voltage applied to the ESA electrodes, the instrument scans through the all energies between 8.0 and 33,500 eV per charge. Electrons leaving the ESA strike a conversion dynode and generate a signal on a MCP. The azimuthal position of the is measured by sixteen anodes, and this is used to determine the azimuthal direction of the particle's velocity. The ion pass through a time of flight mass spectrometer, but their azimuthal directions are similarly measured by sixteen anodes. In practice, full spectra with 128 energy, 16 elevation and 16 azimuthal bins are not returned to Earth. Instead, for the data discussed here, the spectra are collapsed to 64 energies, 4 elevations and 4 azimuths by summing groups of adjacent bins.

After leaving the ESA, ions are accelerated across a -8 kV potential and into the time of flight system. They enter the system by passing through a thin (~70 A) carbon foil. The 8 kV post acceleration is intended to reduce the range of energies within the system (from a factor of 4200 to a factor of 5.2) and to minimize energy loss and scattering as the ions pass through the foil. The ions may leave the foil as positive ions, neutral atoms or negative ions. Typically 5—25% of the exiting particles are positive ions. For the species discussed in this paper, only protons and molybdenum form stable negative ions, with a yield of approximately 5% for the energies in question. The ions eject secondary electrons from the foil, and very heavy atoms such as xenon may also eject carbon atoms or ions from the foil. The electric fields within the TOF chamber accelerate the secondary electrons downward, where they hit a 16-anode MCP to generate a "start" signal.

Figure 3 is a diagram of the trajectories of ions and secondary electrons within the TOF chamber. An ion which exits the foil as a neutral will then cross the time of flight chamber and strike the central, "stop" detector. The time of flight, measured with 0.75 ns precession determines the velocity of the particle, and therefore its energy per mass. Due to the uncertainty in the particle's energy, and energy loss and scattering in the foil, these "straight through" (ST) peaks in the TOF spectra are relatively broad, and the resulting mass resolution is approximately 10% FWHM.

If a particle leaves the foil as a positive ion, it is reflected by the electric field within the chamber and strikes the top of the system. The top of the TOF system is held at −8 kV while the bottom is at +8 kV. The instrument is designed so that the electric field within the chamber is upward and has a strength which increases linearly with distance. The motion of an ion in such a field is described by simple harmonic motion and the time of flight depends only on the mass of the particle. After striking the top of the chamber, the ion produces another secondary electron, which is accelerated across the chamber and strikes the stop detector. Since the time of flight is independent of the particle's energy, and unaffected by scattering in the foil, these "linear electric field" (LEF) peaks are narrower than the ST peaks.

Effects of TOF Entrance Foil In the process of crossing the entrance foil, the ions scatter and loose energy. This shifts the TOF peaks to longer times, and increases the width of the peaks. Heavily scattered particles may also produce "ghost" peaks, e.g. by striking the side of the chamber and producing a secondary electron which then hits the stop detector. To minimize these effects, an extremely thin foil is used, and the ions are accelerated before hitting the foil. Despite this, transmission through the foil is significant for particles with an energy under 1 kV per nucleon and a major issue for particles with less than 0.25 kV per nucleon. To account for the effects of the foil on a wide variety of species, we have use Monte Carlo simulations using the TRIM software package (SRIM 2000, v.2000.39) developed by IBM-Research.[5]

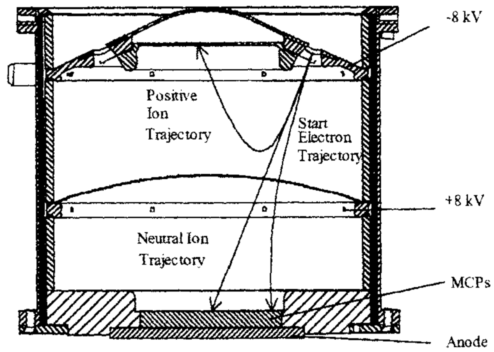

Figure 3: Trajectories of particles within the time of flight system

The foil used by the PEPE instrument has a nominally thickness of 0.5 μg/cm^2, however the actual thickness is probably greater. Tests of 0.5 μg/cm^2 foils from the same manufacturer, conducted as part of developing the CAPS instrument on Cassini, show that the actual thickness is closer to 1 μg/cm^2 and that the foil contains a significant amount of adsorbed water.[6] Pre-flight calibration data of the PEPE time of flight system is available for five species at three energies. We have computer simulated time of flight spectra for these species and energies, and iterated by varying the thickness and water abundance of the model foil, until we obtained the χ^2 best fit to the calibration data. Further simulations were then used to calculate the straight through times of flight for other species (e.g. Xe and Mo) which were not included in the pre-flight calibrations. Figure 4 shows example of such a simulated spectrum.

Overview of PEPE Observations

During 1999, 899 hours of PEPE data were obtained with the IPS operating. IPS substantially alters the spacecraft charge and electron sheath, but has little effect on higher energy particles such as

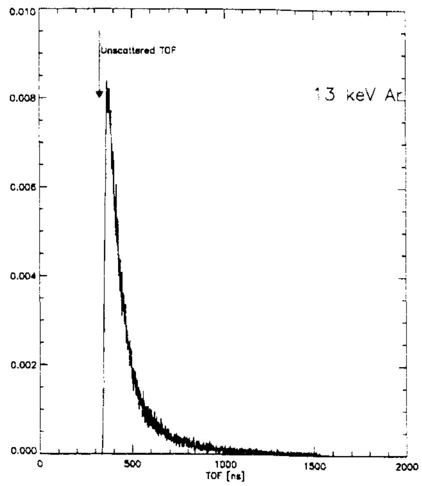

Figure 4: Simulated TOF spectra of Ar+ entering the foil with an energy of 13 keV

the solar wind protons and alpha particles. The presence of sheath electrons in the PEPE observations show that the spacecraft is positively charged with respect to the solar wind, at the location of the PEPE instrument. The data show a high flux of low energy ions, with a energy distribution roughly approximated by a power law, and extending to approximately 50 eV. On January 22, 1999, the instrument collected data over its full energy range, 9 eV to 33.5 keV, while the IPS operated at a low thrust level. The fluxes were sufficiently high to cause extremely high noise levels in the TOF system (due to coincident starts and stops from multiple particles in flight at the same time) and concerns over instrument safety. In all the subsequent data when the IPS was on, PEPE stepped through the range 20 eV to 33.5 keV. This protects the instrument from the high fluxes below 20 eV, but also means the data only sample the higher energy tail of the IPS-related plasma.

IPS-related Ion Fluxes

Over the 899 hours of data, the average flux of ions below 100 eV was 1.5×10^8 particles/cm^2/s. If these particles were all Mo^+, this would result in an accumulation rate of 2.8 nm/kHr. Since the instrument only observed particles with energies over 20 eV, the actual accumulation rate would higher by an uncertain but potentially large factor. This suggests that the particles are not Mo^+. The shadowed IDS contamination monitor showed an average 2.6 nm/kHr of Mo accumulation at a location much closer to the IPS beam than PEPE. Either the particles are not Mo^+, or the deposition rate of Mo^+ higher at greater distances from the IPS.

Correlation with IPS Thrust Level

Figure 5 shows the ion flux at energies between 20 and 100 eV versus IPS thrust level for all data obtained in 1999, while figure 6 is a plot of ion flux and thrust level versus time. The maximum flux is clearly determined by the thrust level. Despite this, the observed flux may be substantially lower than this maximum. The variability may be smaller than these data suggest: The bulk of the ions are below PEPE's 20 eV threshold, and a small change in the ions' energy distribution could cause a major change in the flux of ions above 20 eV. Other possible sources of variability, independent of thrust level, include changes in spacecraft potential and/or solar wind conditions.

Time Variability

The most systematic sort of time variability in the PEPE data occurs after the start of IPS thrusting. As plotted in figure 7, the ion flux is initially low, and gradually rises over the course of several hours. Roughly 4 hours are required for the flux to reach its equilibrium value. This gradual rise and the ~5 hour time scale are typical of all the IPS starts observed, although figure 7 only shows one example. We do not have any clear explanation for this gradual increase; there are no obvious processes or time constants in the IPS which vary on this time scale.

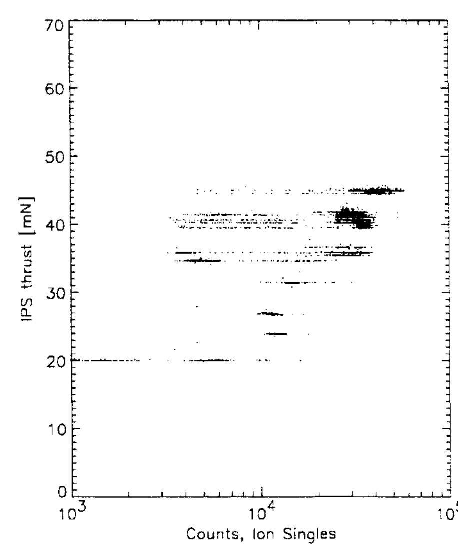

Figure 5: IPS thrust level versus <100 eV ion flux

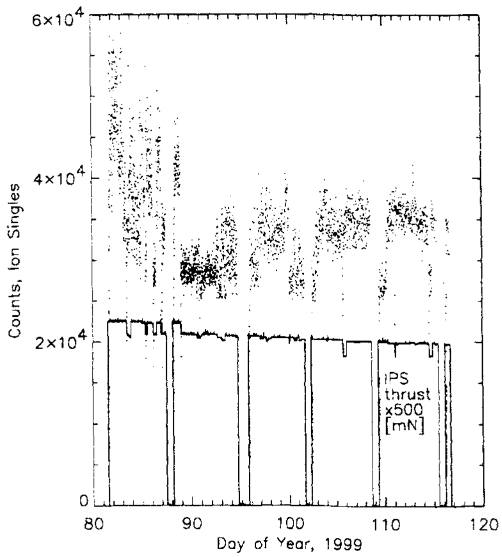

Figure 6: Ion flux and thrust level (in mN) versus time

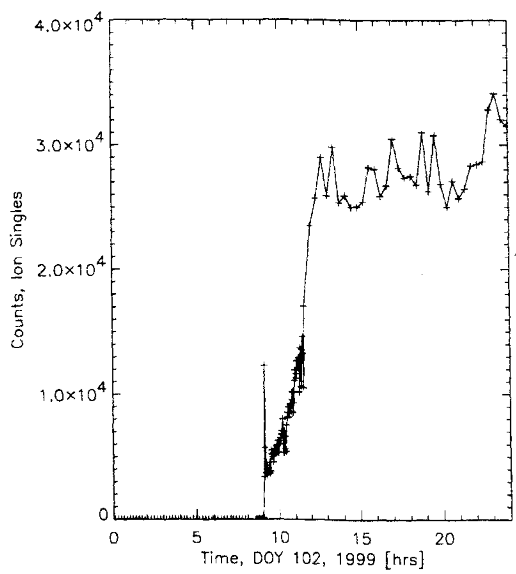

Figure 7: Rise in ion flux following an IPS start

Composition of IPS-related Ions

Xe^+, Xe^{++}, and Mo^+

The IPS-related ions produce several features in the time of flight spectra. Figure 8 shows the TOF spectra with the IPS on and off, averaged over all data obtained in 1999. Easily identified in both spectra are the three peaks of H^+ (exiting the foil as H^-, H^0 and H^+), and the two peaks of He^{++} (exiting the foil as He^0 and He^+). The operation of the IPS causes a substantial increase in the background at all times of flight, but the main solar wind peaks are still easily identified.

The IPS-related ions also produce a broad peak centered on channel 850 (~640 ns). The species producing this peak are difficult to identify: Simulations of Xe and Mo transmission through the entrance foil show that both species would be very heavily scattered and would lose a large fraction of their energy. This results in very broad peaks, and for Xe^+, most of the particles' time of flight would exceed the maximum 1536 ns of the instrument's timer. Finally, the ions produce additional peaks, one at the expected LEF time of flight for C^+, and a peak or shoulder on the 640 ns peak, near channel 450 (340 ns). Simulations show that these heavy ions would also sputter carbon off the entrance foil, and sputtered C^+ would produce the observed peak. Sputtered, neutral carbon would have too low an energy, and therefore too long a time of flight, to appear in the spectra.

The peak at channel 850 is at the expected Mo^+ LEF time of flight. In addition, Mo leaving the foil as a negative ion could potentially explain the peak near channel 450. Unfortunately, the exact time of flight for Mo^- is not known from calibration data, and will require additional ray tracing to calculate. In any case, there are difficulties with identifying these peaks as Mo. As noted above, the total flux is too high to be Mo, unless the flux is substantially higher at the location of PEPE compared to the IDS contamination monitor.

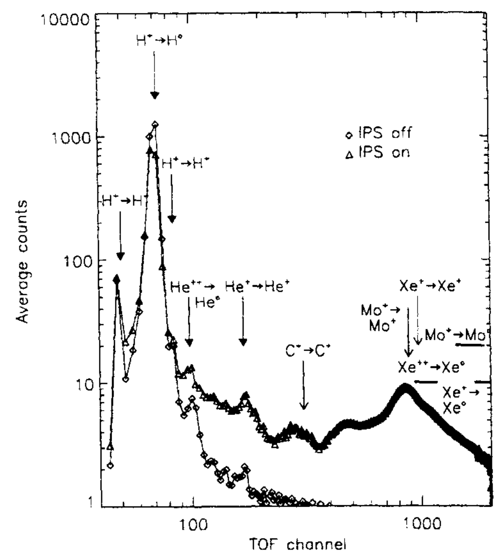

Figure 8: TOF spectra with IPS on and off, all data from 1999

Further, there is no evidence of a straight through Mo peak, which should be present and have a higher amplitude than the Mo^+ and Mo^- peaks.

The expected LEF time of flight for Xe is also close to the observed peak, so the observations may indicate a combination of Xe and Mo. The straight through peaks of Xe^{++} and Xe^+ are all at significantly larger times of flight than the observed peak. It is worth noting that the transmission of Xe^{++} through the foil is substantially more efficient than Xe^+; when accelerated through a 8 kV potential, Xe^{++} gains 16 keV. The higher energy per nucleon results in a substantially less scattering and energy loss. As a result, even if Xe^{++} were less abundant than Xe^+, it could appear dominant in the observed time of flight spectra. Due to the large amount of scattering, some Xe^+ could strike the sides of the chamber and produce a ghost peak at channel 450. As with determining the location of the Mo^- peak, this possibility would require substantial, additional ray tracing to resolve. At present, we can not clearly determine whether the observed ions are Mo^+, Xe^+ or Xe^{++}.

Hydrazine-related N^+

In addition to the species seen whenever the IPS is operating, PEPE has also observed N^+ when both IPS and the spacecraft's hydrazine attitude control thrusters are active. Spectrograms of six IPS starts are shown in figure 9. In five of the six cases, the IPS start is followed by a number of busts with an apparently nosy energy distribution. This type of signature is commonly seen during IPS starts, but has been observed at other times as well. We have found that these events only occur when both IPS and the RCS thrusters are active. In the case of the April, 13, 1999 start, this coincides specifically with use of the Z-thrusters, and the plasma signature disappears when attitude control is transferred from RCS to the IPS gimbals. The apparently noisy signature is due to the time resolution of the PEPE instrument. Since PEPE scans through elevations and energies, these measurements are made sequentially. Each energy bin in figure 9 was measured 1 second after the next higher energy bin. As a result, any plasma appearing or disappearing on shorter time scales would produce an apparently noisy spectra. The DS1 RCS thrusters typically fire in approximately 10 ms bursts.

Figure 10 shows the time of flight spectra from these periods, in an average weighted by the total duration of all RCS firings during the measurement. Figure 11 shows the spectrum of these events after subtracting the background from the IPS-related ions. The peak for these ions is at the estimated time of flight for straight through N^+. We interpret this as nitrogen ions generated with the combustion products of hydrazine enter the IPS Xe^+ and undergo charge exchange reactions. To the resolution of our TOF data, these could also be NH^+ molecular ions. Although the flux of N^+ ions is very high during these events, the total flux integrated over all of 1999 is many orders of magnitude less than that of the other, IPS-related ions, due to the very short duty cycle and duration of these events.

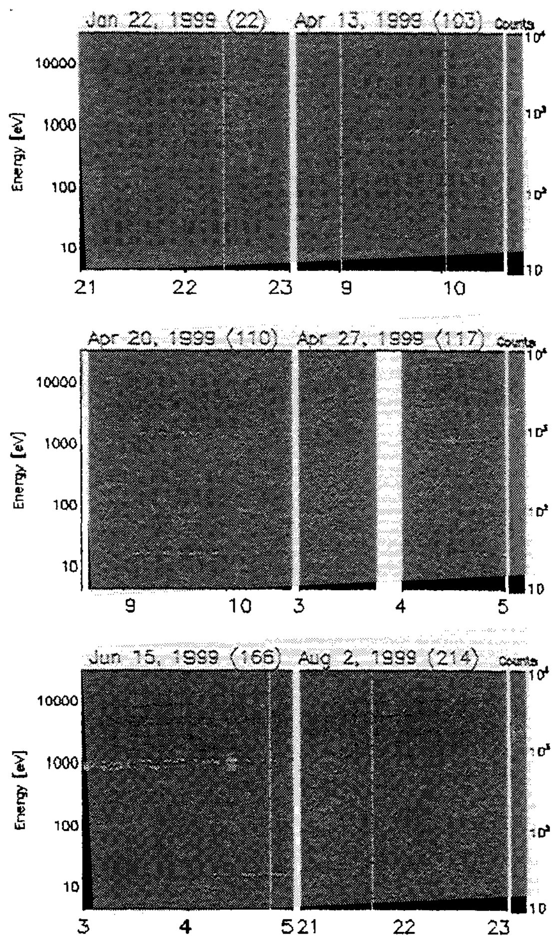

Figure 9: Energy-time spectrograms of six IPS starts

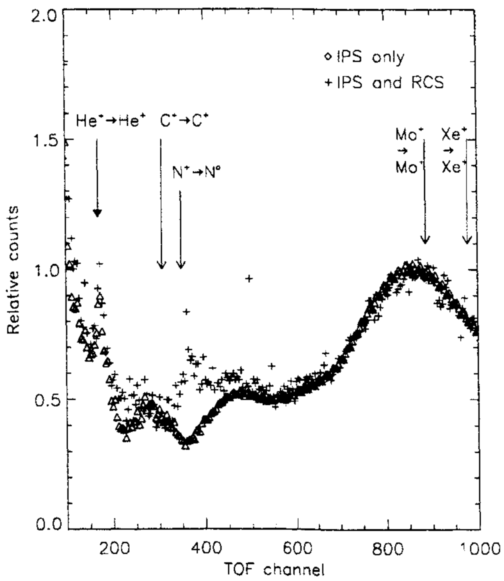

Figure 10: TOF spectra while IPS operating, with and without RCS activity

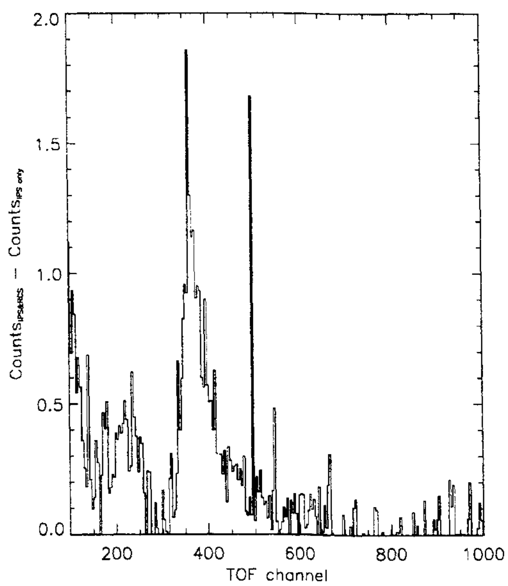

Figure 11: TOF spectra of RCS/IPS events with IPS background subtracted

[1] Polk, J., et al., "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission: Overview and Initial Results", AIAA Paper 99-2274, June 1999.

[2] Wang, J., et al., "Deep Space One Investigations of Ion Propulsion Plasma Environment", *J. Spacecraft and Rockets, 37*, 545, 2000.

[3] Brinza, D., et al., "Deep Space One Investigations of Ion Propulsion Contamination: Overview and Initial Results", AIAA Paper 2000-0465, Jan. 2000.

[4] Young, D. T., et al., "Plasma Experiment for Planetary Exploration", to be submitted to *Space Science Reviews*, 2001.

[5] Ziegler, J. F., et al., *The Stopping and Range of Ions in Solids*, Pergamon Press, New York, 1985.

[6] Baragiola, R. A., personal communication, 2000.