

DEEP SPACE 1 ENCOUNTER WITH COMET BORRELLY: COMPOSITION MEASUREMENTS BY THE PEPE ION MASS SPECTROMETER

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On 22 September 2001 Deep Space One (DS1) successfully encountered Comet Borrelly at a distance of closest approach of 2171 km. DS1 is, after Giotto, the second spacecraft bearing an ion-mass-resolving instrument to explore the plasma environment of a comet. This mass spectrometer, called the Plasma Experiment for Planetary Exploration (PEPE) [1], is capable of resolving the energy, angle of incidence, and mass composition of a wide range of solar system plasmas.

The miniaturized mass analyzer included in PEPE (see figure 1) is a time-of-flight (TOF) mass spectrometer capable of determining the mass-per-charge (M/Q) of plasma ions by both conventional TOF analysis and by linear electric field (LEF) TOF analysis [2,3]. Ions entering PEPE are first E/Q-selected by a top-hat electrostatic analyzer (not shown) and are then accelerated into a thin carbon foil. The atomic species exiting the foil form neutrals, positive ions

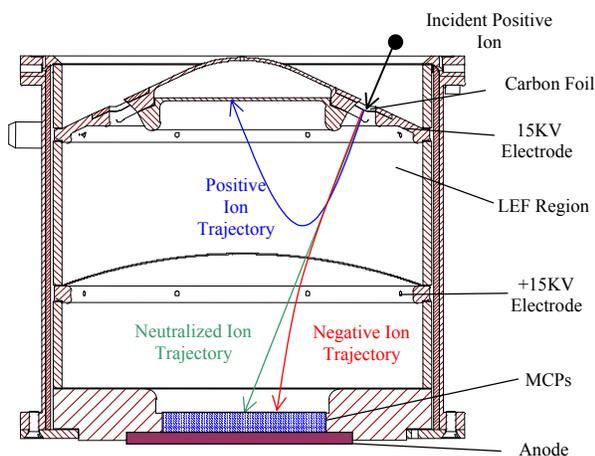


Figure 1. Detail of PEPE time-of-flight spectrometer. A linear electric field (LEF) exists between the -15 kV and +15 kV electrodes. This field turns positive ions, causing them to describe a trajectory whose timing only depends on the ion mass, but not energy, resulting in enhanced mass resolution. The spectrometer has cylindrical symmetry, thus capable of simultaneously detecting particles through 360°. Note that during the Borrelly encounter, PEPE was operated with -11 kV on the negative electrode and +5 kV on the positive electrode, resulting in a factor of two lower mass resolution.

and, for incident O- and C-containing ions, negative ions. The relative abundance of these ion products is a function of the incident ion species and energy. Thus for a given incident ion species, the TOF spectrum, can contain up to three peaks.

In Figure 2 we show a portion of the time-of-flight spectrum measured by PEPE during the seven minutes of closest approach to the comet. The range of channels shown here, from TOF channel 150 through channel 400, corresponds to incident C⁺, N⁺, and O⁺, and C, N, and O fragments from CH_n⁻, NH_n⁻, and OH_n-group molecular ions that dissociate in the foil.

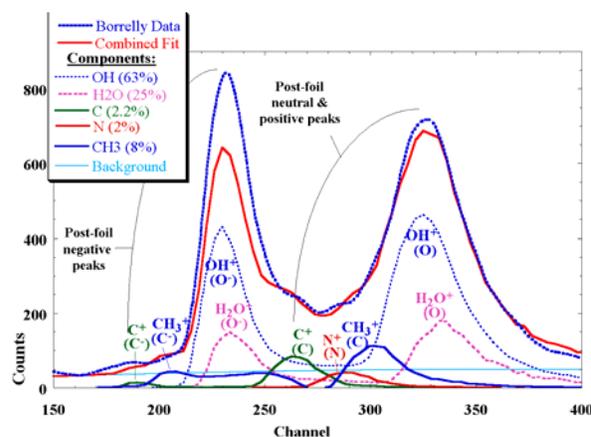


Figure 2. The uppermost dotted line represents the smoothed observations of the time-of-flight spectra from channel 150 through channel 400 as observed by PEPE during the seven minutes of closest-approach to Comet Borrelly (2171 km < r < 4000 km). Also shown are the results of simulations of the instrument response to incident C, N, O, H atomic and molecular ions. PEPE converts singly-charged positive ions into negative, neutral, and positive atomic ions, resulting in multiple peaks for each constituent. Each contributing peak is labeled by the incident ion, and in parenthesis, the post-foil product ion

One can clearly see the multiple peak contributions from a single incident ion species. For example, incident OH⁺ ions contribute significantly to the two major peaks near channels 220-230 and 320-330, respectively. The former peak is formed by negative O ions exiting the foil as a result of the molecular dissociation

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and charge conversion of OH^+ within the foil, and the latter peak is due to neutral O produced in the same manner. OH^+ also forms positive O ions, which contribute weakly to the tail of the neutral peak (not labeled). In the same manner, H_2O^+ contributes significantly to the O^- and O^0 peaks. The negative-ion peak for carbon is less significant than for oxygen, while nitrogen yields no negative peak.

The best fit to the Borrelly closest approach water-group data yields $\sim 65\%$ OH^+ , $\sim 25\%$ H_2O^+ , $\sim 2.5\%$ C^+ , $\sim 2\%$ N^+ , and $\sim 8\%$ CH_3^+ . The estimated uncertainty on these values is ± 20 percentage points on OH^+ and H_2O^+ , and approximately a factor of 2 on the others. The figure shows the fit given by this composition, as well as the contributions from each constituent. Note that CH_2^+ could be substituted for nitrogen, though the negative-peak region appears slightly better fit by N^+ (which makes no negative peak contribution). Likewise, the CH_3^+ could also be fit by NH^+ , but the negative-peak region appears to favor at least a significant contribution from CH_3^+ . The ions O^+ , H_3O^+ , and CH^+ are likely present, but at abundances below clear detection.

Data from the Giotto flyby of comet Halley [4,5] indicate that the relative composition of water group ions change significantly as a function of the distance from the comet. At the Halley closest approach and out to about 20,000 km, H_3O^+ was the dominant ion, while at intermediate distances H_2O^+ and OH^+ were dominant, and beyond ~ 10 km, O^+ was dominant, consistent with production of H_3O^+ due to molecular collisions close to the nucleus, and with progressive photodissociation as the molecules traveled outward from the nucleus. The Borrelly closest approach distance of 2171 km was somewhat farther than the Halley flyby, but the main difference is the relative activities of the two comets. Because H_3O^+ is collisionally produced from H_2O , the relative absence of H_3O^+ measured by PEPE is consistent with the much lower activity of Borrelly compared with Halley.

The minor peaks from 12 to 15 amu also differ significantly from those observed at Halley. At closest approach the Giotto mass 15 peak was more than an order of magnitude higher than the mass 14 peak, and $\geq 98\%$ of these species were attributed to CH_3^+ [6]. If the inferred Borrelly nitrogen abundance is accurate, it reveals a higher nitrogen-to-carbon ratio than at Halley. Altwegg et al [6] discussed the source of the significant CH_3^+ abundance seen especially at the closest approach distances of Halley, and concluded that its steep radial density gradient was inconsistent with methane as its source. They concluded rather that it was from a quasi-point source of CH_2 at the nucleus.

The CH_2 molecule is rapidly dissociated, but it has a higher proton affinity than water, thereby readily gaining a proton in a collisional environment near the nucleus. The PEPE data reported here is the first confirmation of the relatively high CH_3^+ abundance in cometary clouds. However, it is interesting that the abundance of this species is elevated even in the relative absence of H_3O^+ .

References: [1] D. T. Young, et al., (2001) *Space Science Reviews*, in press. [2] D. J. McComas and J. E. Nordholt (1990) *Rev. Sci. Instrum.*, 61, 3095. [3] D. J. McComas, J. E. Nordholt, S. J. Bame, B. L. Barraclough, and J. T. Gosling, (1990) *Proc. Nat. Acad. Sci., USA*, 87, 5925. [4] H. Balsiger, et al. (1986) *Nature* 321, 330. [5] K. Altwegg, H. Balsiger, J. Geiss, R. Goldstein, W.-H. Ip, A. Meier, M. Neugebauer, H. Rosenbauer, E. Shelley (1993) *Astron. Astrophys.* 279, 260, (1993). [6] K. Altwegg, H. Balsiger, J. Geiss (1994) *Astron. Astrophys.* 290, 318.