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NOTE

Observation by Pioneer 7 of He^+ in the Distant Coma of Halley's Comet

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During the approach of Pioneer 7 to a distance of 12.1 × 10^6 km from the nucleus of Comet P/Halley on March 20, 1986, features were observed in plasma analyzer data that we interpret as He^+ produced by charge exchange of solar wind He^{++} with neutral cometary material. The maximum flux of the He^+ was observed several hours after the closest approach of the spacecraft to the nucleus, and is unexpectedly large. Remarkable large discontinuous flux changes were also observed. © 1987 Academic Press, Inc.

The Pioneer 7 spacecraft was launched in 1966, with a scientific payload that included plasma and energetic particle experiments for synoptic study of the interplanetary medium (Corliss 1972). The heliocentric orbit is very near the ecliptic plane, with an aphelion distance of 1.126 AU. While an initial objective was to collect complete scientific data for at least 6 months, it has been possible to acquire some additional data even up to the present time. The spacecraft solar cell power has degraded over the years to the point that the full complement of experiments cannot be operated simultaneously. In this note, data are presented and discussed that were collected near the nucleus of Halley's comet on March 20, 1986, by the Ames plasma analyzer.

The Pioneer 7 Ames plasma probe experiment contains a 90-deg deflection, quadrispherical electrostatic analyzer with a fairly large acceptance geometry (Smith and Day 1971) and provides nearly omnidirectional sensitivity to plasma fluxes. The energy range covered for protons is from 230 to 9900 eV, in 16 logarithmically spaced steps. At the telemetry rates possible during March 1986, only the peak flux during one time base interval of the experiment (~0.71 sec) at each energy step, together with directional information, is available. Analysis of data obtained following failure of the Sun sensor (in 1969) showed that the plasma analyzer data collection, as expected, was no longer synchronized with viewing of the solar direction by the experiment. However, the

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experiment's internal timing does permit viewing the solar wind about 70% of the time. Flux samples obtained when the solar wind direction is not viewed can be identified both by fluxes lower than expected, as well as by peak flux selection by the experiment in a direction from which the solar wind is not expected. Complete spectra can be constructed using samples from the solar wind direction from preceding or following spectra.

Meridian and ecliptic plane projections of the trajectory of Pioneer 7 past Comet P/Halley, which was encountered by chance, are given in a comet centered, ecliptic oriented coordinate system, in Fig. 1. The $+Z$ axis is toward ecliptic north, the X axis is parallel to the ecliptic plane, with the Sun in the XZ plane, and the $+X$ axis toward the Sun. The Y axis completes a right-handed, orthogonal system. The closest approach to the nucleus occurred at ~1455 UT on March 20, 1986, at a distance of 12.1×10^6 km. The Sun–comet–spacecraft angle was 111 deg then, and the distance of the comet from the Sun was 1.00 AU. One sees that the spacecraft first was downstream from the comet, relatively close to the tail. Subsequently, the nucleus moved past the spacecraft, as the comet continued along its outbound trajectory. Nearly 70 hr of tracking were provided for Pioneer 7 during March 18 to 22.

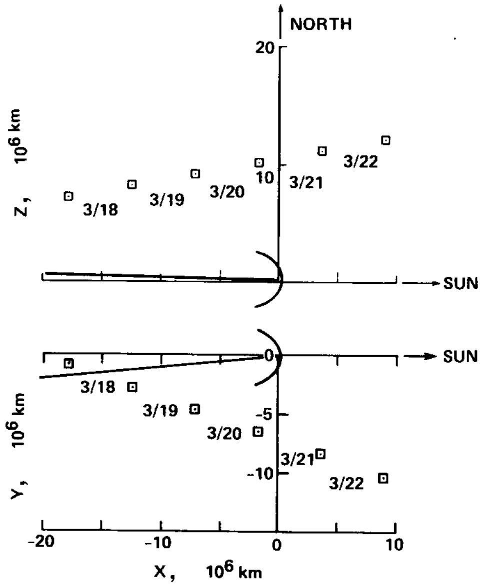

FIG. 1. Meridian and ecliptic plane projections of the Pioneer 7 trajectory near Halley's comet, in a comet-centered, ecliptic oriented coordinate system. Symbols indicate the beginning of each day, and dates are given. The location of the bow wave is indicated, as reported from data from other spacecraft (Gringauz *et al.* 1986, Mukai *et al.* 1986, Neubauer *et al.* 1986, Galeev *et al.* 1986). A tail axis is indicated, assuming radial outflow of solar wind from the Sun. The solar direction and tail axis diverge appreciably from the orientations shown on the meridian plane projection, after March 14.

Typically in the solar wind, the plasma analyzer detects solar wind protons and He^{++}. Occasionally coronal heavy ions (Bame 1983) appear just above the measurement threshold. Just past the closest approach of Pioneer 7 to the nucleus of the comet, in addition to the solar wind proton peak and He^{++} peak, or "shelf," a third isolated peak, at four times the E/q for protons, or somewhat higher than that, appeared in the E/q spectra for several hours. An example of a spectrum displaying this third peak is given in Fig. 2; here the solar wind proton and He^{++} responses may be considered typical, although the relative abundance of He^{++} is high. The amplitude of the third peak varies with time as discussed later. The data of Fig. 2 correspond to a solar wind proton speed and number density of ~330 km/sec and 10./cm^3, respectively. Detection of solar wind He^{+} and minor heavy ions might be expected near the location of the third peak. However, this Pioneer 7 experiment has not observed those previously at fluxes higher than about 10% of the highest values detected near the comet nucleus that are presented and discussed here. By analogy with results of Balsiger *et al.* (1986), who identified cometary pickup protons in mass analyzed data from the Giotto high energy range mass spectrometer (HERS), obtained about $6\frac{1}{2}$ days previously near the comet, this third peak in the Pioneer 7 plasma

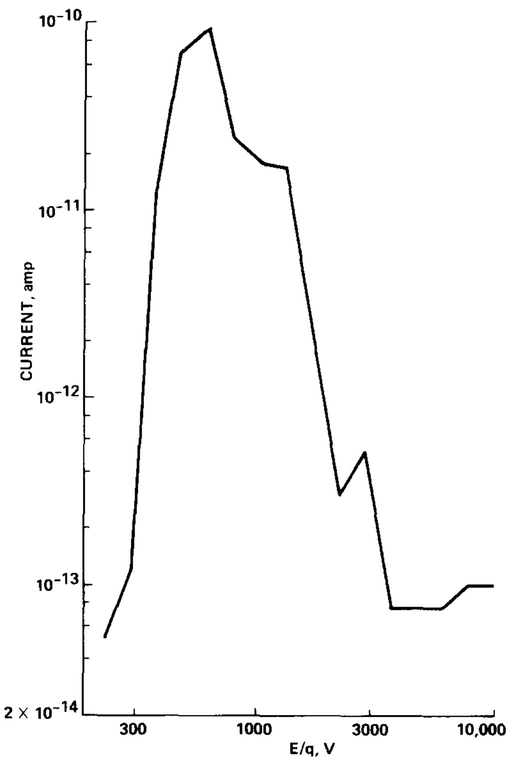

FIG. 2. Pioneer 7 solar wind spectrum observed at 1937 UT, March 20, 1986. The values at 380 and 610 eV are averages from the preceding and following spectra. The solar wind proton peak is at ~550 eV, the He^{++} "shelf" is near 1200 eV, and the peak identified as He^+ is near 2900 eV.

spectra might be attributed to cometary pickup protons. Out to $\sim 2 \times 10^6$ km from the comet, Giotto HERS data showed pickup protons at about twice the solar wind speed in the solar wind direction, as well as in a shell distribution in velocity space (see, for example, Gary *et al.* 1986), from three-dimensional data (see also Neugebauer *et al.* 1986). Such protons originate from photolysis of cometary water, and charge exchange of the resulting hydrogen with the solar wind, and then undergo acceleration by the motional electric field of the solar wind. Two-dimensional measurements of cometary pickup protons out to 9.7 to 9.0×10^6 km from Halley's comet were also made at the Suisei spacecraft about 13½ days previously (Terasawa *et al.* 1986). The distant detections of pickup protons reported from Suisei data were somewhat downstream in the solar wind from the comet nucleus, similar to the Pioneer 7 observations discussed in this note. The Suisei observations were east of the nucleus, rather than north and west of it, where the Pioneer 7 data were acquired.

An alternative identification for the third peak in the Pioneer 7 E/q spectra is He^+ which has undergone charge exchange with hydrogen in the coma, from the normal fully ionized state in the solar wind. Indeed, the sizes of hydrogen comae at 1 AU are expected to exceed 10^7 km (Johnstone 1985). Figure 3 gives density estimates for this third peak, assuming that their distribution in velocity space is peaked, like that of solar wind particles, and that they are singly charged. He^{++} densities estimated for the same time interval are also given in Fig. 3; both plots give peak values sampled during 0.71-sec intervals. The mean He^+ density appears to be ~0.4% of the He^{++} density. Flux decreases of both ions appear to occur coincidentally near 1825, 1905, and 1950 UT-ERT. The peak He^+ density reported does not appear to coincide with any particularly prominent feature in the record for He^{++}.

Balsiger *et al.* (1986) reported detection of $M/q = 4$ material by the Giotto HERS, within 10^5 km of comet Halley, and Shelley *et al.* (1986) analyzed HERS data on He^{++} and He^+ within the Halley bow shock (10^6 km). The observed flux at 10^5 km would correspond to He^+ produced from charge exchange of about 30% of the incoming solar wind He^{++}, and ~1% at 10^6 km. If most of the hydrogen coma is not charge exchanged within about 10^7 km of the nucleus, then a simple, steady spherical flow model of the coma would give an inverse-square distance profile for the H density, and a rough calculation then shows that in this region the He^+ intensity should approximately vary as the inverse first power of probe–comet separation. Thus, at

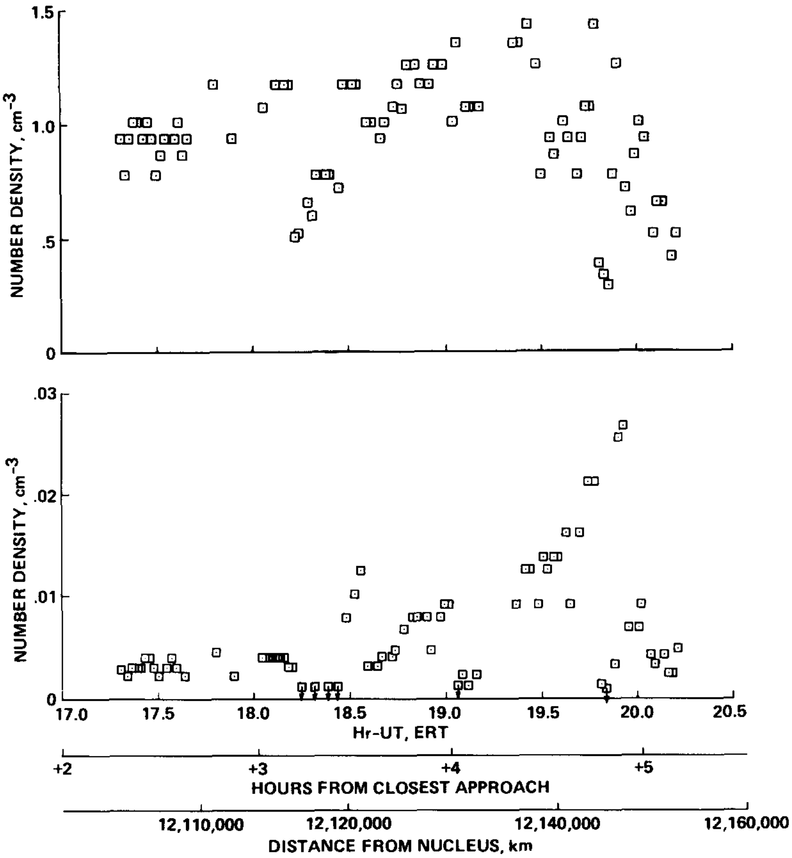

FIG. 3. Time history of helium ion densities inferred from Pioneer 7 plasma analyzer data obtained near Halley's comet, on March 20, 1986 (He^{++}, upper; He^{+}, lower).

the location of Pioneer 7, we expect a He^{+} flux of order 10 times weaker than near the comet's bow shock. The highest flux observed by Pioneer 7 is of order 70 times greater than this expected value, which suggests that Pioneer 7 passed through a region of unusually dense cometary material near the time of closest approach. This interpretation is consistent with the relatively abrupt onset and termination of the highest $E/q = 4$ peaks. Furthermore, the solar wind density (protons and He^{++}) appears to have been greater at the time of these measurements, than during the Giotto encounter.

If these Pioneer 7 detections are of a uniformly filled shell of pickup protons in velocity space, approximating those analyzed by Neugebauer *et al.* (1986), the densities presented on Fig. 3 would be lower than the correct values by a factor of ~6 (including a factor of ~13–14 to account for the limited solid angle sampled by the experiment). Also, the proton densities, excluding the peak values, would be about 30 times greater than the corresponding results of Terasawa *et al.* (1986). However, these Pioneer 7 data do not appear to represent detection of a shell in velocity space, since the instrument reports only the peak flux during its time base interval at each energy step. As a result, the instrument would be expected to detect such a shell at random energies between a low value corresponding to the speed of cometary gas relative to the spacecraft, and one which corresponds to protons with a speed twice that of the solar wind. In fact, there is no evidence that the "third peak" shifts toward lower energies; hence these data are more indicative of an isolated peak in velocity space, at somewhat more than four times the E/q for protons, although measurements of the complete velocity space distribution are not available from this experiment at this distance from Earth. Immediately before and after the times of the figure, collection of plasma spectra was interrupted for one-hour periods in order to measure energetic particle fluxes. Other than during the time of Fig. 3, the only such detections were a few very low fluxes beginning at 1517 UT-ERT (on March 20).

The more rapid variations with time of the He^+ fluxes plotted in Fig. 3 might be associated with nonuniform emission of water from the comet nucleus. The most prominent change of the solar wind He^{++} fluxes during the same time intervals occurs just prior to the maximum He^+ flux observed, when a disappearance of the He^+ is accompanied by temporary decreases of the solar wind proton (−40%) and He^{++} (−80%) fluxes. The solar wind protons, and particularly the He^{++}, however, do appear to be hotter when these He^+ fluxes are higher. Usually it has been assumed that plasma will be heated in association with the pickup of newly ionized atoms. Hence greater heating should occur where the coma contains a region of enhanced density, but the mechanism for this heating, in the case of the solar wind, does not appear to be identified yet. (This subject is often discussed in connection with interstellar neutral atoms in the vicinity of the Sun (cf. Feldman 1979).)

In conclusion, plasma data collected from Pioneer 7 when it approached to a distance of 12.1×10^6 km from the nucleus of Comet P/Halley on March 20, 1986, briefly indicate the presence of relatively rapidly varying fluxes of He^+ that could arise from charge exchange of solar wind He^{++} with cometary gas. The fluxes observed appear to be about 50% higher than peak values for solar wind minor ions, for up to 5 hr. In addition, there are remarkable, relatively brief excursions up to values an order of magnitude higher.

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