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A TEST PARTICLE MODEL OF PICKUP IONS AT COMET HALLEY

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Abstract. A test particle treatment is used to investigate some of the details of the pickup cometary ions observed at comet Halley. The effects of the large-scale magnetic and motional electric fields, as described by an MHD model of the comet, produce the characteristic V shape seen in Giotto observations in simulated energy-time spectrograms. It is demonstrated that scattering produced by the addition of magnetic field fluctuations can obscure the tendency of the large-scale field to deflect energetic ions picked up in the outer coma from the tail axis. The fact that the V is so clearly observed in the Giotto spectrogram thus suggests that although scattering must be invoked to explain the isotropic pitch angle distributions and highest energy ions, it does not have a major effect on the overall pickup ion spectrum.

Introduction

Comets provide one of the major laboratories for the study of the interaction of cold, heavy ions with a flowing, magnetized plasma. The acceleration or "pickup" of these ions is known to involve both large-scale and turbulent electromagnetic fields. Key findings of the recent spacecraft encounters with comets (see Geophysical Research Letters, volume 13, March 1986; Science, volume 232, April 1986; Nature, volume 321, May 15-21, 1986) include both the verification of Alfvén's [1957] first qualitative picture of the effect of a comet on the large-scale interplanetary magnetic field, and the discovery that the field and plasma in the vicinity of the comet are more disturbed than in the surrounding medium.

Winske et al. [1985], Wu et al. [1986], Sagdeev et al. [1987], and Buti and Lakhina [1987] have recently discussed their views on the causes and effects of these turbulent or wave fields which stem from plasma instabilities connected with the production of the cold cometary ions in the flowing solar wind. The initiation of these instabilities depends on the large-scale field direction with respect to the background flow [cf. Omidi and Winske, 1986]. The ions are subsequently constrained to move as the wave fields in combination with the large-scale fields dictate. A few may undergo Fermi acceleration to energies much greater than that which the large-scale convection electric field can provide [cf. Ip and Axford, 1986]. Price and Wu [1987] used test particle calculations to study the formation of shell-like distribution functions that will occur in conjunction with this energization. In contrast, Kimmel et al. [1987], neglected instabilities and their resultant field perturbations and examined the characteristics of the effects of the large-scale field alone on picked-up test particles. This latter study demonstrated that certain observational features of the pickup ions at comet Giacobini-Zinner were possibly consistent with large-scale field effects. Of course, their model could not produce the extremely energetic particle population [cf. Hynds et al., 1986].

Because little is known about the global distribution of the turbulent fields, studies which start with the macroscopic field structure provide a baseline from which the effects of these fields can be deduced. For example, as in some earlier findings of Wallis and Johnstone [1982], Kimmel et al. [1987] found that the highest energy ions which are picked up in the outer coma tend to follow trajectories that diverge from the tail axis. In contrast, ions picked up in the inner parts of the coma where the flow is stagnating stay cold and focus into a tail current sheet. Although Kimmel et al.'s results were for Giacobini-Zinner, where ICE observations (see Geophysical Research Letters, volume 13, May 1986) had shown the presence of a large level of turbulence in the magnetic field and plasma at the spacecraft, these authors noted that the observed double peaks in the time series of the pickup ion flux could have been produced by the aforementioned diverging ion trajectories. The macroscopic draping of the magnetic field, in combination with stagnating flow, disperses the most energetic pickup ions into two apparent streams separated by the tail axis. (It should be noted, however, that Daly et al. [1986], have proposed an alternate explanation based on the behavior of ions near a current sheet.)

Whereas the ICE encounter with Giacobini-Zinner was a result of redirecting a spacecraft designed for solar wind measurements, the planned Giotto and Vega comet missions to Halley included instrumentation specifically geared toward pickup ion detection. In particular, Johnstone et al. [1986] contributed a plasma analyzer covering the

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range 0.1-100 keV in several look directions. Their observations provided the impetus to apply the test particle techniques described by Kimmel et al. to the pickup ions at comet Halley. The results of this simulation, reported here, help to illustrate which features of the observed ions necessitate the consideration of plasma instabilities and microscopic fields.

Description of the Test Particle Model

For the purpose of the present calculation, the velocity and magnetic field structure from an MHD model of comet Halley, analogous to that used for Giacobini-Zinner [Fedder et al., 1986], was employed. The results from such models consist of values of the single fluid variables $\bar{v}$, ρ, p and $\bar{B}$ (velocity, mass density, thermal pressure and magnetic field) at points within a three-dimensional grid box. In this case, the simulation box of (33 x 29 x 29) points extends from 2×10^6 km upstream to 7×10^6 km downstream of the nucleus at the origin and cross axis dimensions of $\pm 1.2 \times 10^6$ km. The mass production rate of 6×10^{29} s^{-1} used in the MHD calculation is consistent with the value derived for Halley during the Giotto encounter [cf. Gringauz et al., 1986]. Adopted upstream solar-wind parameters were velocity 380 km s^{-1}, (proton) number density 10 cm^{-3}, and interplanetary magnetic field strength, 7 nT, roughly in accordance with observations. Thus the field compression and draping and flow stagnation are expected to be accurate except for the regions near the nucleus (e.g., the contact surface) and close to the tail axis where the spatial resolution of the model ($\sim 10^4$ km grid spacing) ceases to be sufficient.

The model is constrained to have the upstream magnetic field perpendicular to the flow. Although this deviates somewhat from the observed direction [cf. Neubauer et al., 1986], which has a significant radial component, the observations also show evidence of temporal variations of the upstream perpendicular field, which may obscure any organizing effect that the radial component has on the particles. Moreover, it is considered that the major features of the solar wind interaction for any upstream field with a significant perpendicular component are about the same. Figure 1 shows the magnetic field geometry, in the plane containing the upstream field and the nucleus, superposed on the streamlines of the flow. The sharp draping of the cometary field lines attests to the degree of stagnation of the only slightly deviated flow. Notice that the Cartesian coordinates are defined such that x is along the comet-Sun line, the upstream magnetic field is in the direction of z, and y is normal to the plane of the diagram.

The test particles used for this simulation are singly ionized water (mass 18) ions launched from logarithmically spaced radial shells of starting points. The starting points are approximately randomly scattered on these shells. Their surface densities are based on the radial production function

$$Q \propto \frac{1}{r^2} \exp\left(-^{r}/10^6 \text{ km}\right)$$

representing a cloud of neutrals expanding

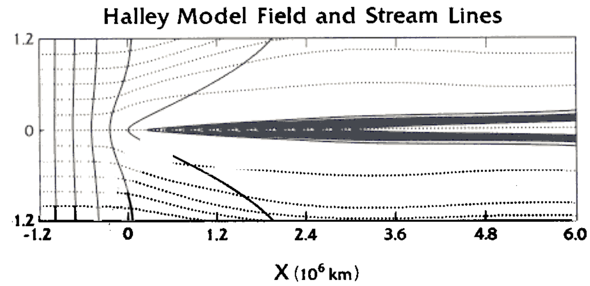

Fig. 1. Selected magnetic field lines (solid) and single fluid stream lines (dotted) from the MHD model of comet Halley used in the present test particle calculations. In the cross section shown, the nucleus is at the origin, and the upstream magnetic field lies in the plane of the figure.

spherically at 1 km s^{-1} and subject to a time constant for ionization of 10^6 s. About 4500 particles were launched for each case study. Their trajectories were followed by solving the equation of motion using a fourth-order Runge-Kutta scheme. Linear interpolation was used to obtain values of the magnetic field and convection electric field between grid points of the MHD computation grid. For the purpose of orientation, Figure 2 shows the starting point distribution and a few ion trajectories. The latter illustrate the previously mentioned tendency for the ions launched in the outer coma to converge toward it. The trajectory of the Giotto spacecraft is also indicated.

Particle energy spectra at specific points are obtained by dividing the simulation box into 10^5-km-sided cubes and determining the statistics for all particles leaving the cube.

Results

Since Johnstone et al. [1986] chose to present their results in the form of color energy-time spectrograms of flux in the energy range from 0.1 to 100 keV, the results of the present test particle model of Halley pickup ions are presented in similar form. As in Kimmel et al., pseudo time series of the energy spectra are constructed by choosing the sequence of the aforementioned cubes within the simulation box intersected by the spacecraft trajectory. The energy spectra are here made up of either numbers of particles or the particles' total kinetic energy associated with each cube, binned in logarithmic energy intervals of $\Delta \log E = 0.1$, for the detector range of 0.1 keV to 100 keV. The counting statistics are then color coded (in gray scale), approximately logarithmically, and plotted in spectrogram form, assuming that the spacecraft spends equal time in each cube. Detector aperture restrictions can be folded into these spectrograms by including only those particles with trajectories having local directions within specific solid angle ranges.

In Figures 3 and 4, a selection of simulated "spectrograms" are displayed. The energy resolution was determined on the basis of the statistics, and was chosen so as to provide

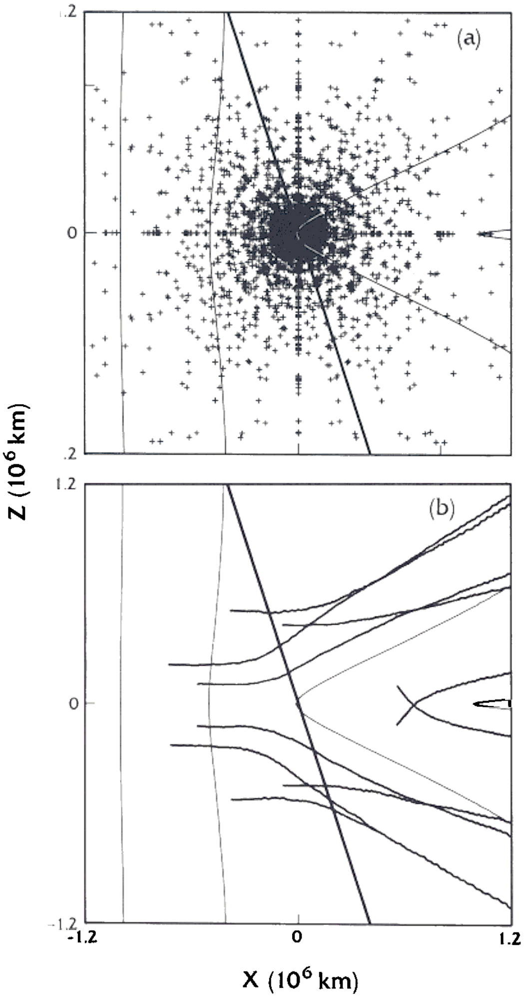

Fig. 2. (a) Starting points for water ions in the MHD model, superposed on some draped magnetic field lines. The trajectory of the Giotto spacecraft is also shown for the assumption that Giotto intersected the comet in the plane of the upstream field. (b) Examples of ion trajectories showing the two characteristic behaviors (divergence from the tail axis and convergence toward the tail axis).

detail while at the same time maintaining a reasonably smooth spectral scope. The particular set of spectrograms in Figure 3 is for the omnidirectional number flux out of each cube. In order to illustrate the effect of spacecraft encounter geometry on the observations, the spacecraft "trajectory" has been assumed to be located at several different distances from the nucleus. These various intersections are all parallel to the Giotto spacecraft trajectory and in the plane of the nucleus. In this case, the upstream magnetic field is also in the same plane. The characteristic V shape of these spectrogams, produced by the convolution of the ion production function, background convection electric field and the magnetic field, echoes that seen in the data. Moreover, it is apparent that the V shape is less distinct near the nucleus and upstream than it is far downstream. The effect of rotating the magnetic field by 90° with respect to the spacecraft trajectory is illustrated by Figure 4a. The distinctive V trace remains, but weakens due to the fact that fewer pickup ions are channeled into the perpendicular plane than the parallel plane [cf. Kimmel et al., 1987].

The Johnstone et al. detector on Giotto actually observed the pickup ion populations in narrow solid angle ranges [Thomsen et al., 1987]. Moreover, the spectrograms that were presented in the literature [eg. in Johnstone et al., 1986] are more analogous to energy flux than number flux spectrograms (A. Coates, personal communication, 1987). Consequently, several illustrative examples were generated using total energy for the color scale, and including restrictions on the angles of the counted trajectories. Because a relatively small number of ions were traced in the present model, it was necessary to use "simulation detector" windows at least ~30° wide to get a reasonable number of particles in the model spectrogram bins. Figure 4b shows the results for the Giotto trajectory in a plane parallel to the upstream field. As might be expected, for an acceptance window of 60°-90° with respect to the direction of the spacecraft trajectory, the spectrogram trace becomes somewhat narrower. This behavior is roughly consistent with what was observed by the Giotto detectors of 10° width both near the spacecraft spin plane and in the 50°-60° range shown by Johnstone et al. In contrast, the simulation predicts no flux for a window at 0°-30° centered on the spacecraft spin axis, which is oriented along the trajectory, while Giotto detected pickup ions in that direction in a much narrower window. The weighting of the spectrogram counts by energy intensifies the high-energy part of the spectrograms, as one might expect.

The detection of pickup particles by Giotto instruments, in directions essentially parallel to the upstream magnetic field, has been previously noted as evidence of scattering of the ions by waves and turbulence in the cometary magnetosheath [cf. Johnstone et al., 1986]. This expectation is, not surprisingly, borne out by the results of the present simulation. However, the degree of scattering is evidently not sufficient to greatly influence the appearance of pickup particle energy spectra in the modeled range of energy below 100 keV.

To investigate the effect that such waves can have on the general morphology of the pickup ions, fluctuations in the magnetic field were introduced into the algorithm. Because the details of the waves or turbulence are not expected to be an important consideration with regard to gross effects on the pickup ions, with the possible exception of the ~$1/r^2$ dependence of wave amplitude on the radial distance r from the nucleus [Galeev et al., 1986], a simple representation was adopted. It was assumed that the scattering was caused by convected fluctuations in the magnetic field which are described by the three vector components

$$\delta B_x = A \sin a$$

$$\delta B_y = A \sin a$$

$$\delta B_z = A \cos a$$

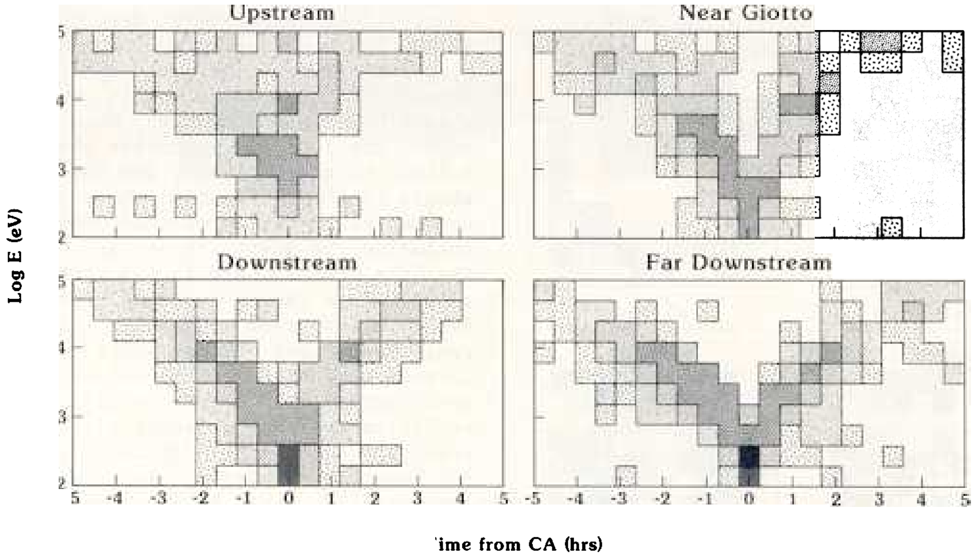

Fig. 3. Simulated "number flux" spectrograms of Halley pickup ions at various distances, determined by translating the Giotto trajectory parallel to itself by -10^5 km (upstream), $+10^5$ km (downstream) and $+5\times10^5$ km (far downstream), compared to the result for Giotto's location. (The darkest to lightest colors (shading) denote counts >100, 61-100, 31-60, 11-30, 1-10, respec tively.) These were all obtained by presuming that Giotto's path lay in the plane of the upstream magnetic field.

where $A = A_0\ (10^{12}\ \text{km}^2/r^2)$ but $A = 0$ inside $r=2\times10^5$ km (since the waves are observed to decrease in this inner region according to the spectral measurements of Schwingenschuh et al. [1986] on the VEGA space- craft) and $a = k_x x + k_y y + v_x t$. Here A is the local wave amplitude, A_0 is the upstream amplitude, k_x and k_y are wave vectors calculated so that $k_x=2\pi/(\tau v_x)$, and $k_y = -k_x$. The definition of k_x allows one to specify a characteristic convected wave period τ for the entire ineraction region (the background velocity is practically in the x direction), while the condition on k_y ensures that the perturbation magnetic field is divergence-free. Because

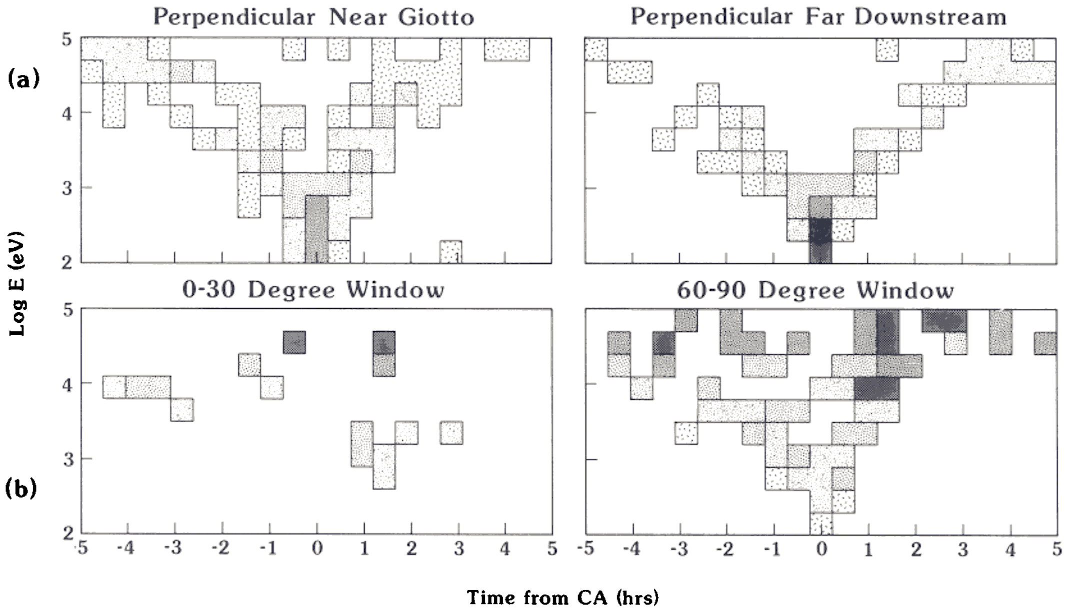

Fig. 4. (a) Same as the examples for Giotto's location and far downstream in Figure 3, except that the space-craft trajectory has been rotated 90° about the Sun-comet axis to an orientation perpendicular to the upstream field. (b) Same as Figure 3 near Giotto, but the intensity denotes "energy" flux, which is more analogous to the observations published by Johnstone et al. [1986], and the angular acceptance is restricted to windows 30° wide with respect to directions centered 15° and 75° from the spacecraft velocity vector.

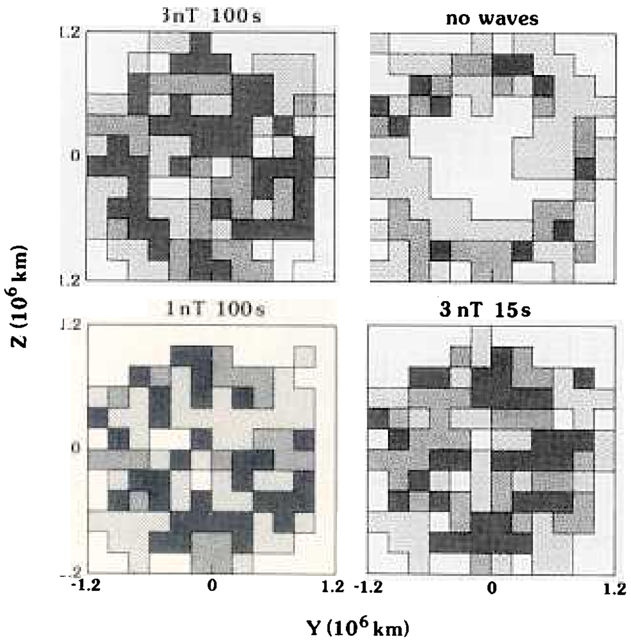

Fig. 5. "Slices" through the MHD simulation box, showing where outer coma ions intersect the plane near the nucleus without scattering and with scattering (see text). The labels designate the assumed upstream wave amplitude A_0 and period τ.

simplicity is desired for the model representation of cometary waves, it is assumed that the wave coordinate system does not depend on the local magnetic field. Rather, the fluctuations behave independently, with x, y and z defined as for the MHD simulation. Consequently, local transverse and compressional components are determined only by the direction of the underlying large-scale field (see Figure 1). However, it has been empirically determined that variations of the description of the field fluctuations do not produce significantly different results than the case described here.

The present type of test particle simulation is best suited for the illustration of morphological effects of scattering on the spatial distribution of the particles. (The practical number of particles is much too small to allow analysis of the Fermi acceleration process, for example.) To that end, and to minimize the computational expense, several limited simulations were carried out in which only the particles in the outer coma ($r>5\times10^5$ km) were launched in wave fields of different apparent period τ and upstream amplitude A_0. "Slices" were then taken through the ion trajectories in the simulation box, at various downstream distances x from the nucleus, to determine how the spatial spread of the ionized particles from the outer coma changes with the introduction of scattering.

Intuitively, one might expect to find that scattering not only isotropizes the particles, but also couples them more closely to the motion of the scatterers, which in this case are the magnetic fluctuations moving in the -x direction. Since the ions born in the outer coma in the scatter-free case diverge from the tail axis (see Figure 2), and therefore from the relatively straight stream lines (see Figure 1), slices through the simulation box in the tail should show a hole in the center. When scattering is added, the ions' trajectories should begin to follow the stream lines, and therefore the hole should fill in. Figure 5 shows some results from several case studies of the number flux, including the scatter-free case. As anticipated, the hole that appears in the center for the scatter-free (no waves) case becomes filled in for even low-level amplitudes (~1 nT) and for a range of periods of the "waves" (0.01s to 100-s periods were tried). The effect on the spectrograms, since the energies of these particles are only slightly altered by scattering, is to fill in the V (e.g., in Figure 3). Fluctuating plasma velocities, as are observed [cf. Baker et al., 1986, Gosling et al., 1986], should merely enhance this effect. Thus either locally generated or convected waves and turbulence both manifest themselves in the level of particle flux at the upstream pickup ion energy within the region near the tail axis.

Discussion

The extent to which the V in the spectrograms clearly appears in the Johnstone et el., [1986] data attests to the fact that, although the isotropizing effects of plasma turbulence are present, scattering by plasma and field turbulence at comet Halley is not a primary consideration in the description of the bulk of the pickup ion population. However, the energetic ion flux which appears within the V is probably caused by scattering of the ions picked up in the outer coma. As noted above, the present simulation does not treat a sufficient number of particles to illustrate the development of a very energetic ion component from Fermi-type acceleration process. Nevertheless, the calculation provides a reasonable facsimile of, and explanation for, the gross appearance of the Giotto pickup ion data below an energy of ~100 keV.

In conclusion, a test particle model of the pickup ion population at comet Halley has been constructed using an MHD model of the background magnetic field and flow. Without consideration of scattering of the ions by plasma and field turbulence or of in- stabilities of the particle distribution function, one can produce a fairly satisfying approximation of the V-shaped energy-time spectrograms obtained by Johnstone et al. [1986] on Giotto. The addition of magnetic field fluctuations in the model shows that scattering of the ions picked up in the outer coma can explain the flux of particles observed within the V. This treatment thus provides a global perspective on the importance of scattering in the explanation of the general features of Halley's major pickup ion population.

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