GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO 11, PAGES 1809-1812, OCTOBER 1990

HYPERVELOCITY DUST PARTICLE IMPACTS OBSERVED BY THE GIOTTO MAGNETOMETER AND PLASMA EXPERIMENTS

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Abstract. We report thirteen very short events in the magnetic field of the inner magnetic pile-up region of comet Halley observed by the Giotto magnetometer experiment together with simultaneous plasma data obtained by the Johnstone plasma analyzer and the ion mass spectrometer experiments. The events are due to dust impacts in the milligram range on the spacecraft at the relative velocity between the cometary dust and the spacecraft of 68 km/sec. They are generally consistent with dust impact events derived from spacecraft attitude perturbations by the Giotto camera [Curdt and Keller, private communication]. Their characteristic shape generally involves a sudden decrease in magnetic field magnitude, a subsequent overshoot beyond initial field values and an asymptotic approach to the initial field somewhat reminiscent of the magnetic field signature after the AMPTE releases in the solar wind. These observations give a new way of analyzing ultra-fast dust particles incident on a spacecraft.

Introduction

One of the primary objectives of the cometary missions to comet P/Halley was the investigation of the dust environment. This was accomplished successfully by the dust experiments PIA and DIDSY on Giotto [Kissel et al., 1986a; Mc Donnell et al., 1986] and on VEGA [Vaisberg et al., 1986; Mazets et al., 1986; Simpson et al., 1986; Kissel et al., 1986b] which were designed to record individual dust particles. In addition to the instruments designed to record single dust impacts the spatial distribution of dust can be investigated by optical means [Levasseur-Regourd et al., 1986].

Apart from these dedicated dust instruments, dust impacts can also be observed by instruments which were not originally designed for such observations of dust. For example, the resulting changes in the spacecraft attitude can be detected by an onboard camera and the charge pulses produced can be observed by the electric antennas of plasma wave experiments [Gurnett et al., 1983].

In this paper we shall present observations of magnetic field disturbances and the plasma signatures produced by dust impacts.

A dust impact generally occurred on the dust shield of Giotto or one of the protruding appendages [Reinhard, 1986] during the Halley encounter. Because of the high relative velocity an impact leads to a complete vaporization and partial ionization of the projectile and some of the target material. This leads to an expanding plasma cloud which produces magnetic field disturbances similar to the AMPTE releases. Using this mechanism dust particles can be detected as magnetic field disturbances only when an ambient magnetic field is present. This field should then be as high as possible to obtain a large impact signal. Hence the inner pile-up region around comet Halley [Neubauer et al., 1986] is particularly promising for this purpose because of the high magnetic field and close distance. We shall also present data from the IMS-HERS and the JPA plasma experiments on Giotto which complement the magnetic field observations in an important way.

Observations

The magnetic field observations were obtained by the Giotto magnetometer experiment which has been described elsewhere [Neubauer et al., 1987]. The data are measured at a sampling rate of 28.24 vectors per second corresponding to $\Delta t = 35.417$ msec between successive vectors. The data have been corrected for a slowly varying spacecraft field and for the magnetic field of the despin motor. Since the observations reported here have a frequency spectrum extending up to the Nyqvist frequency of the instrumentation at 14.12 Hz the convolution of the signal with the transfer function of the anti-aliasing filter of the magnetometer implies some signal distortion. For example, the transfer function produces a phase distortion of 90 degrees and an amplitude reduction by a factor of $\sqrt{2}$ near the Nyqvist frequency. This distortion decreases rapidly towards lower frequencies.

The transfer function of the instrument was corrected exactly for frequencies at $f \approx 0$ Hz of the magnetic field in the non-rotating inertial frame of reference. For any quantitative evaluation of the observed time variations an appropriate deconvolution will be necessary.

The plasma observations were obtained by the HERS sensor system of the ion mass spectrometer (IMS) experiment [Balsiger et al, 1986] and the fast ion sensor of the Johnstone plasma analyzer (JPA) experiment [Johnstone et al., 1986] onboard Giotto. Since a full experiment cycle takes 16 seconds for the HERS-IMS experiment, the plasma observations consist of the readings of the mass channels, energy and directional channels which happened to be scanned during the duration of the event. For the JPA instrument the situation is the same with an internal cycle time of the spin period of four seconds.

We have scanned the high time-resolution magnetic field data for conspicuous reversible events of short duration in the time interval from 23:58:00 UT SCET (Spacecraft event time) on March 13, 1986, to 00:08:00 UT SCET on March 14, 1986, corresponding to distances from the comet less than about 20500 km. A large number of events was obtained, where most of them are characterised by an abrupt and reversible deviation from a smooth variation in the magnetic field in one sample only. We have then further considered only those events with deviations in magnitude from a general trend by more than 4 nT as particularly clear signatures. In this scan the cavity region

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Paper number 90GL01524
0094-8276/90/90GL-01524$03.00

has been excluded because of the reasons given in the introduction. An example of the events identified is given in Figure 1. The magnetic field data are displayed in Halley-centered solar-ecliptic coordinates (HSE-coordinates). The sharp dip in the magnetic field suggests that the data have been undersampled. Therefore the dip could well be deeper than apparent in the data. The event shown in Figure 1 started at the time 00:00:46.9 on March 14, 1986.

Table 1 lists all the thirteen events discovered in the magnetic field data. The general behavior is an initial decrease with a subsequent recovery and sometimes an overshoot. The second column of the table shows the time of the minimum magnetic field. Event six has been disturbed by interference from the stepper motors of the Halley Multicolor Camera (HMC). Event eleven shows no minimum. The time of the maximum is given. A minimum could also have occurred in this case but missed because of the low sampling rate or the convolution with the anti-aliasing filter.

The third column compares our events with the only published list of dust impacts near the comet [Poster presentation by W. Curdt and H.U. Keller, Bamberg 1989] which also contained mass estimates. Their dust impact events were detected by dynamical perturbations of the spacecraft detected by the camera HMC. After closest approach at 00:03:02 UT SCET no comparison can be made because the camera stopped its operations. Four HMC events occurred inside the cavity where the magnetometer is "blind". There were six HMC events before entry into the cavity, two of which, i.e. events one and six, agree with our events. Event 1 was analyzed in some detail already using IMS, JPA and DIDSY observations [Goldstein et al., private communication, 1989]. Events one and six are characterised by masses greater than 5 mg according to Curdt and Keller. Three of the HMC events not seen by the magnetometer were due to much smaller particles in the milligram range. The only impact due to a large particle not seen by the magnetometer occurred approximately 103 seconds before closest approach.

The fourth column gives the distance whereas the column labelled "Type" describes the phenomenological type. When the decrease to the minimum occurred in one step it is called abrupt (a). Otherwise it is labelled gradual (g). The field could vary by going down as a rule or by going up in event eleven.

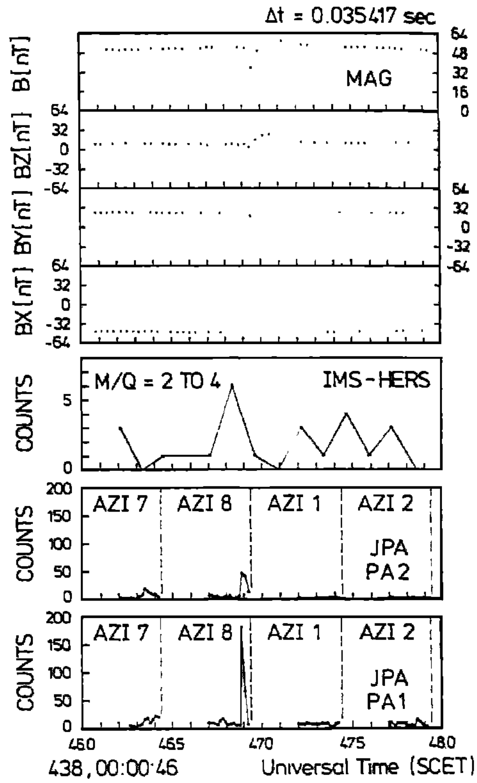

Figure 1: Magnetic field and plasma observations of dust impact event two. The magnetic field vectors are represented in Halley centered solar ecliptic coordinates at a time resolution of 28.24 vectors per second. The data of the ion mass spectrometer HERS sensor system are shown in raw data counts. The peak corresponds to M/Q = 2 presumably H_2^+. The Johnstone plasma analyzer data also given in raw data counts are shown for a spacecraft polar angle range PA 1 pointing towards the comet at 20-72 degrees from the spacecraft - comet line and PA 2 somewhat removed from that direction at 72-124 degrees from the spacecraft - comet line. The vertical dashed lines in the JPA-panels indicate the dividing lines between counts obtained in azimuthal sectors 7, 8, 1 etc. For further discussion see text.

TABLE 1. Dust Impact Events Observed by Giotto Near Closest Approach (For Explanation see Text)

Event Number	Time of UT SCET Minimum	Association With HMC	Association With IMS	Association With JPA	Distance 10^3km	Type	
1	23:59:26.0	yes	yes	yes	14.8	g,	down
2	00:00:47.0	no	yes	yes	9.3	a,	down
3	00:00:58.4	no	yes	"blind"	8.5	a,	down
4	00:01:32.5	no	yes	yes	6.1	a,	down
5	00:01:47.9	no	yes	yes	5.1	a,	down
6	00:01:52.2	yes	yes	yes	4.8	a,	down
7	00:04:02.3	-	-	yes	4.2	g,	down
8	00:04:06.5	-	-	yes	4.5	a,	down
9	00:04:12.2	-	-	yes	4.8	a,	down
10	00:04:19.0	-	-	"blind"	5.3	g,	down
11	(00:04:31.6)	-	-	yes	6.2	a,	up
12	00:04:54.8	-	-	yes	7.7	g,	down
13	00:06:10.7	-	-	yes	12.9	a,	down

We mentioned already that in the latter case a short minimum may have escaped detection because of its small width.

Further important evidence for the nature of the magnetic field events as being due to dust impacts has been obtained by the plasma observations. The IMS-HERS instrument identified all the events from 1 to 6 before it died between events 6 and 7. Figure 1 also shows the IMS-HERS data for event two. The experiment was in the L-mode when the event occurred as a peak in count rate well above the purely ionospheric count rates. The counts shown in Figure 1 give raw counts at M/Q = 2 presumably due to H_2^+.

We note that the background number of counts is much less than one. The number of counts before and after the maximum is typical for the cometary ionosphere at this distance. The accuracy of the time relative to the magnetometer data is probably not better than 0.1 seconds.

All events except for events 3, 4, 6 and 10 were also identified as very short peaks in the energy and azimuth scans of the JPA experiment with a strong undersampling of the plasma cloud spectra. However, for events three and ten the magnetometer times show that the JPA was in the high voltage flyback state which lasts about 16 milliseconds and in which the JPA is "blind". The time interval of "blindness" could be even longer, because the flyback is followed by the high energy spectral counts in the subsequent energy scans starting from 20 keV downwards. If the energy spectrum of the plasma cloud did not extend up to 20 keV the "blind" interval could have lasted longer. Thus given the identification by the IMS-HERS these events have the same signatures as the other events. The situation is different for events four and six which are characterised by increased count rates for almost a spin period in contrast to the duration of a few 10 milliseconds in the other cases. They may therefore constitute a different type of event.

For our example in Figure 1 the counts in the polar angle interval PA 1 pointing towards the comet and in the adjacent interval PA 2 are given as a function of time. Whereas the measurements in the polar angle intervals PA 1, PA 2 etc. are done simultaneously, the azimuthal angles are scanned by the rotation of the spacecraft with two energy scans one after another superimposed in each azimuthal bin. Thus at a given time in Figure 1 in every polar angle interval the counts correspond to just one azimuthal angle interval and one energy channel. With the two energy scans per azimuthal bin separated by 0.25 seconds the counts given are the sum of the counts around the time of the plot and 0.25 seconds, i.e. a sixteenth spin rotation, earlier. The azimuthal bins seven and eight partly shown in Figure 1 are followed by azimuthal bin one in which the experiment aperture looks in the solar direction. The data of all events are consistent with the picture of a plasma cloud with particles coming from the comet at all azimuthal angles and in a broad range of energies. Hence the azimuthal bin of the measurement does not exclude the presence of particles in other directions. Also the energy channels excited are a consequence of the experiment cycle and do not indicate a narrow energy spectrum but rather a short time duration. With the event occurring in two consecutive energy bins it must have occurred around the dividing time 46.92 s or 0.25 seconds earlier in this picture.

A few words on the relative timing of the experiments are warranted because the plasma experiments measure in spin-synchronization and the magnetometer measures in telemetry time synchronization. Because the magnetometer experiment also transmits the angle of rotation from the last sun reference pulse, the times of occurrence of the sun reference pulse have been taken as an accurate means to synchronize the data.

Discussion

We have detected thirteen reversible magnetic field and plasma events of very short duration in the inner magnetic pile-up region of comet Halley at distances of less than 20500 km. They can be clearly distinguished from camera interference signals because of the clear periodicity of the latter signals and their special form. We see no possibility to explain these events by plasma dynamics unrelated to dust except perhaps for the broad events four and six which have a broad plasma signature. The dust impact nature of the events has been confirmed by comparison with plasma observations and attitude changes observed by the camera [Curdt and Keller, private communication] and in the case of event one by comparison with the DIDSY experiment [R. Goldstein, private communication, 1989].

The phenomenology of an event is exemplified by event two in Figure 1 and can be described as follows: A short pulse in the plasma count rates is followed first by a decrease in magnetic field magnitude, an overshoot and an asymptotic approach to the undisturbed magnetic field. The magnetic field behavior is similar to the one observed after the AMPTE releases in the solar wind [Lühr et al, 1986].

We propose the following physical scenario for the events with the possible exception of event four: The large relative velocity of an impacting Halley dust particle implies a kinetic energy of 24.4 eV/amu sufficient to vaporize, dissociate and ionize the dust particle and part of the target material. The initial dense plasma cloud expands rapidly with the initial stages described e.g. by Hornung and Drapatz [1981] for dust particles in the milligram range. At the same time the center of gravity of the cloud initially starts to move away from the spacecraft towards the comet with a velocity relative to Giotto which is a large fraction of the initial relative dust spacecraft velocity w = 68.4 km/s. After an initial phase in which the ionization is described by equilibrium conditions the time scale of recombination starts to exceed the expansion scale according to Hornung and Drapatz [1981]. The ionization state is than essentially frozen in. A little later the plasma particles reach the plasma analyzers. When the collision mean free path becomes greater than the cloud diameter the flow will become collisionless. At an even later time the electrons become frozen to the magnetic field. From this time on the magnetic field in the cloud's interior decreases rapidly as observed by the spacecraft inside the cloud. At the same time the ambient magnetic field is piled up at the "bow" of the cloud and the cloud's center of gravity starts to accelerate due to the interaction with the flow of unperturbed ionospheric plasma . Thus the center of gravity of the cloud is initially moving away from the spacecraft followed by a phase when the cloud reverses direction and moves again towards the spacecraft. The overshoot in the magnetic field is observed when the cloud's pile-up region is reached with a subsequent final decrease to the initial ambient field value. A theoretical treatment of this problem is outside the scope of this observational paper and will be reported in the future.

Discussing the events of Table 1 and the HMC events [Curdt and Keller, private communication] we note the following: The attitude disturbance of the spacecraft is determined by the angular momentum of the incident dust particle with respect to the center of gravity of the Giotto spacecraft and the details of the interaction. The angular momentum is given by M d w, where M is the mass and d the distance from the spacecraft axis. Since the relative velocity w is constant the quantity characterising the impact is M d. On the other hand the detection as a magnetic field event requires a large mass of the plasma cloud given by M times the final degree of ionization α. The events one and six can be associated with large mass events observed by HMC or more precisely large products M d. They are also the most dramatic magnetic field events. Events two through five must be characterised by small M d to explain non-detection by the camera but sufficient M α to be detected by the magnetometer. The HMC events not seen as an event in the magnetic field are characterised by small M and therefore M d except for one. In this case the mass determination may be inaccurate or the degree of ionization is unusually low perhaps indicating that the particle consisted of a material with high ionization potential or strong recombination.

Event four because of the long duration of the plasma signal may be due to a plasma dynamics feature of an unidentified nature. Its minimum variance characteristics are consistant with a planar sheet. Combining all the evidence for event six including the analysis by Neubauer [1988] it seems that a weak outward propagating shock occurred almost simultaneoulsy with a dust impact and a camera disturbance.

Summary

We have investigated thirteen reversible magnetic field events of very short duration in the inner magnetic pile-up region of comet Halley at distances less than 20500 km from the comet. Except possibly for two cases these events were accompanied by short ion bursts when observations by the Johnstone plasma analyzer and the ion mass spectrometer on Giotto were available. They are interpreted as the magnetic and plasma signatures of plasma clouds generated by hypervelocity impacts of cometary dust particles on the Giotto spacecraft. This is consistent with attitude disturbances observed by the Giotto camera experiment. The signature of these events in the magnetic field is similar to that of the AMPTE-releases in the solar wind. A quantitative interpretation based on modelling in the future will open a new possibility to diagnose the important kinematic and mass properties of the plasma clouds due to hypervelocity impact.

Acknowledgments.: The work of F.M. Neubauer, K.H. Glassmeier and G. Musmann was supported financially by the German Bundesministerium für Forschung und Technologie. The work by M.H. Acuña and R. Goldstein was supported by NASA. The work by A.J. Coates was supported by the Science and Engineering Research Council of the U.K.

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(Received January 15, 1990;
accepted May 11, 1990