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Macroscopic perturbations of the IMF by P/Halley as seen by the Giotto magnetometer

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Summary. Giotto magnetic field data have been used to analyze the macroscopic field structure in the vicinity of comet P/Halley. During the Giotto flyby at P/Halley the IMF showed quite a stable "away" polarity. Draping of magnetic field lines is clearly observed along the outbound leg of the trajectory. Inside the magnetic pile-up region the field reverses its polarity several times. A symmetry of oppositely magnetized sheets with respect to the nucleus is found and can be explained in terms of convected IMF features.

Key words: Giotto magnetometer observations – magnetic field draping – P/Halley – solar wind interaction

1. Introduction

Some initial results obtained by the Giotto magnetometer in situ measurements have already been published elsewhere (Neubauer et al., 1986). An overview of the magnetic field structure and the major transitions may be found in the paper by Neubauer (1987). In this report we want to show and discuss the macroscopic structure of the magnetic field in the vicinity of comet P/Halley.

Alfvén (1957) first proposed the model of draped magnetic field lines around a cometary obstacle in the solar wind. This model has subsequently been refined by numerical modelling of the solar wind – comet interaction, for a prominent example see Schmidt and Wegmann (1982). These models usually assume a homogeneous interplanetary magnetic field (IMF) and plasma as well as no turbulence or waves which may be caused by the interaction of pick-up ions with the solar wind. Since these ideal conditions are not met in the real solar wind – comet interaction, the measured field will be characterized by IMF structures as well as by features due to the solar wind – comet interaction.

These considerations make an interpretation difficult in spite of the well known nature of solar wind disturbances which have been studied extensively in the past. In addition the solar wind variations which may be particulary complex at sector boundaries (Behannon et al., 1981) will be strongly modified by the interaction with the comet.

On the other hand the magnetic field variations at P/Halley are quite untypical for the solar wind and can therefore be considered as basically due to the comet – solar wind interaction.

We shall then investigate this interaction in two ways. First we shall show, that the large scale structure between the inbound and the outbound foreshock region clearly confirms the draping picture. Second, we use directional discontinuities (DD's) of large angular spread which are obviously part of sector boundaries swept into the cometary plasma region as tracers.

2. Large-scale magnetic field draping

Figure 1 shows 4 min averaged magnetic field unit vectors along the Giotto trajectory, decimated by 2 and projected onto the X–Y plane of the Halley centered Solar Ecliptic system (HSE). Most of the wavelike fluctuations are smoothed out by the averaging (see also Glassmeier et al., 1987). The plot covers the time interval from 15 UT on March 13 to 9 UT on March 14 (all times are SpaceCraft Event Time, SCET). We used unit vectors to make a good representation of directional variations possible, thus the length of a vector is proportional to the cosine of the elevation angle between the vector and the ecliptic. Vectors with an arrow tip point southward, whereas the other point to the north of the ecliptic. We also show parabolic fittings of the bowshock and the pile-up boundary as they are derived in Neubauer (1987).

2.1. *Inbound observations*

The first transition boundary is given by the cometary bowshock. Before crossing the bowshock at approximately 19:23 UT on March 13, there is no indication of a major macroscopic disturbance of the IMF by the comet visible. This may be masked by strong fluctuations of cometary or interplanetary origin, however. The field is characterized by large fluctuations, but the dominant direction is outward.

Crossing the bowshock the dominant IMF direction persists, but the fluctuation level increases. Some sheets with a towards polarity are present and similar structures appear in the solar wind before entering the sheath, so they are probably due to convected IMF features. There is no draping visible in the whole sheath. Any deflection of the magnetic field lines is small and is thus masked by the fluctuations. The boundary of the magnetic pile-up region occurs at 23:30 UT. This boundary is associated with a decrease in variability in magnetic field direction.

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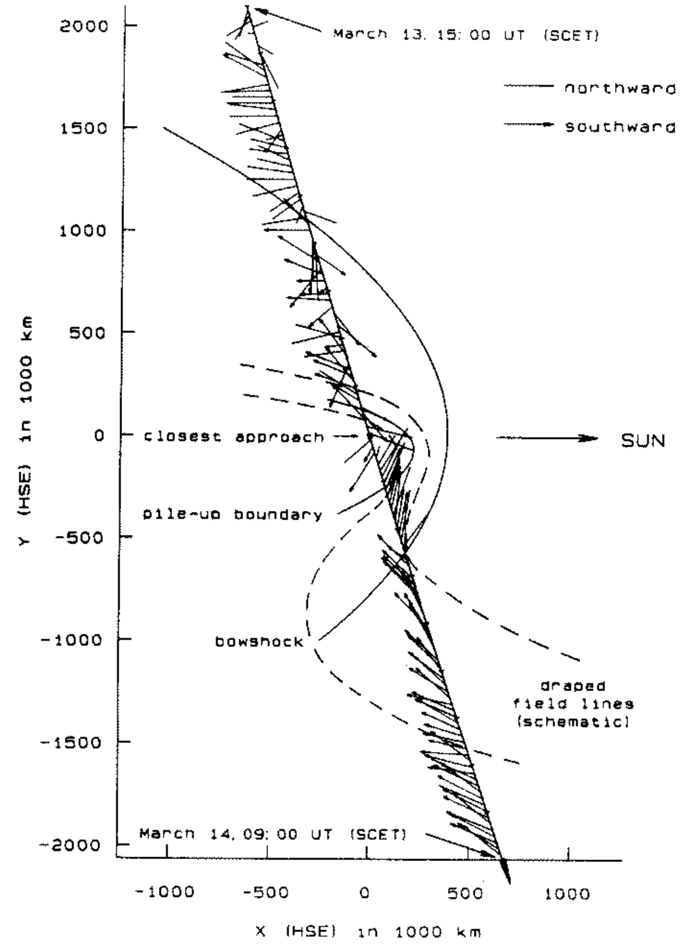

Fig. 1. Four-minute averaged magnetic field unit vectors, decimated by 2 and projected onto the X–Y plane of the Halley Solar Ecliptic System (HSE) from 15 UT on March 13 to 9 UT on March 14. The length of the vectors is proportional to the cosine of the elevation angle with respect to the X–Y plane. Ticmarcs on the trajectory are 1 h apart. The bowshock and the pile-up boundary are indicated together with two schematically drawn draped field lines

2.2. Outbound observations

Following the trajectory from 9 UT on March 14 backwards, the gross structure of the IMF is different compared with the corresponding parts on the inbound leg. The field is smoother and shows less fluctuations. Outside the bowshock the field points steadily away from the sun at an angle between 135° and 165°. Between 2:40 UT and 2:20 UT the field is smoothly deflected towards the sun to an angle of about 60°. The very broad bowshock transition seems to occur between 3:05 UT and 2:30 UT, i.e. between 750000 km and 600000 km from the comet, respectively. The rotation of the IMF in Fig. 1 occurs partly during the broad bowshock structure. Because the deflection persists in the sheath with a gradually decreasing angle, we conclude that this magnetic field deflection clearly reveals draping. Some draped field lines are sketched in the plot. One should observe, that the field along the trajectory is not a snapshot of a spatial structure, but influenced by temporal variations of the IMF during the encounter too. Obviously the IMF conditions before and after the encounter are quite similar, at least with respect to the field polarity. Thus the observed field along the trajectory coincides with the ideal model of a stationary and spatial structure very well.

The outbound pile-up boundary is not very distinct, due to the rather gradual decrease of the field magnitude and some data gaps. Although detailed studies of this boundary still have to be carried out, we consider the discontinuity at 1:07 UT as the best candidate. Well inside this boundary we observe different structures in the magnetic field, which we will discuss next.

3. Observations in the pile-up region

An overview of the magnetic field in the inner region is shown in Fig. 2. Vectors are represented in the same fashion as in Fig. 1. The comet-sun line, also representing the positive X-axis in the HSE system gives some orientation. The time interval is from 23:20 UT on March 13 to 00:31 UT on March 14 and covers most of the pile-up region. A more detailed section is shown in Fig. 3.

On both the inbound and the outbound leg the field consists of sheets, in a way, that the magnetic field directions of adjacent sheets are almost antiparallel. In addition, there is a one to one relationship between the sheets inbound and outbound. Every sheet on either side of the nucleus corresponds to a sheet on the other side. While the magnetic field direction of one sheet is sunward, the field direction of the corresponding sheet points away from the sun. Hence two corresponding sheets on either side of the nucleus may be connected, forming a layer of plasma folded around the nucleus, as indicated in Fig. 3 and precisely as expected in the draping picture.

In Figs. 2 and 3 the discontinuities separating these sheets are labelled with small letters on the inbound leg and correspondingly with capital letters outbound. The innermost discontinuities "a" and "A" are the ionopause. Some minor structures are not shown, so the labelling in the figure has gaps. Many of the field reversals have been analyzed using the minimum variance method and have been named directional discontinuities (DD). Due to camera disturbances inbound and data gaps outbound some of them could not be analyzed with confidence. The intersections of the tangential planes with the X–Y plane are shown in Figs. 2 and 3. No significant changes in the field magnitude are associated with these discontinuities, except for the ionopause and the discontinuity "k" where the pile-up begins. The minimum variance normal magnetic field components show, that many of these DD's may be tangential discontinuities. The main characteristics, i.e. the minimum variance directions, eigenvalue ratios, normal field components and deflection angles are shown in Table 1. In analyzing a strong directional transition we have systematically subdivided the corresponding time interval into subintervals of varying length. Inclusion in Table 1 reguired fulfilment of two conditions. All of the subintervals must approximately yield the same values of ϕ_n and θ_n. The subinterval with the largest value of $\lambda_2/\lambda_3 > 15$ is then shown. The deflection angles in the table should therefore be considered as lower limits, because of the different and in some cases complex structure of these discontinuities.

The strong symmetry between the inbound and outbound leg shows, that these structures are spatial in the comet rest frame, rather than temporal changes during the interval, in which Giotto crossed the inner region. We suggest, that these plasma layers in the pile-up region, characterized by their magnetic field direction, arise from features of the IMF as they are convected into the pile-up region. The solar wind flow in the pile-up region is rapidly slowed and deflected by the mass loading and the ionosphere,

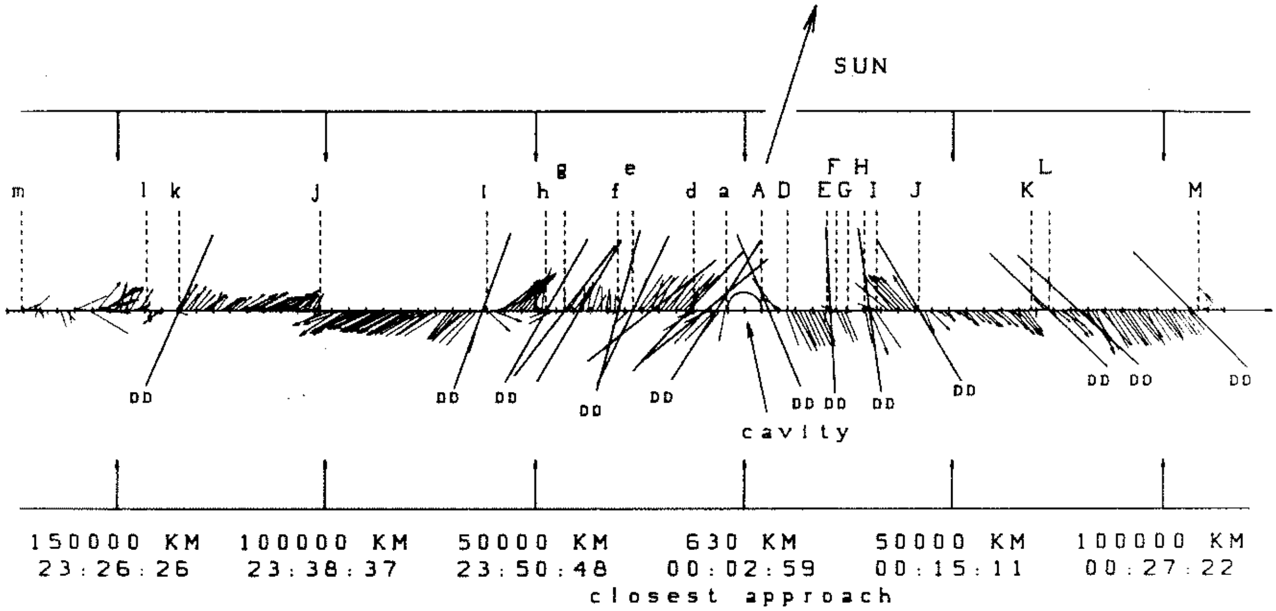

Fig. 2. Projections of 4 s average unit vectors, decimated by 4 onto the *X–Y* plane of the HSE system from 23:20 UT on March 13 to 00:31 UT on March 14. The length of the vectors indicate their elevation angle with respect to the *X–Y* pplane as in Fig. 1. The tics along the trajectory are all 60 s. Dashed lines mark the visible directional discontinuities. The intersection of the normal planes of directional discontinuities, which have been analyzed with the minimum variance method are labelled with "DD"

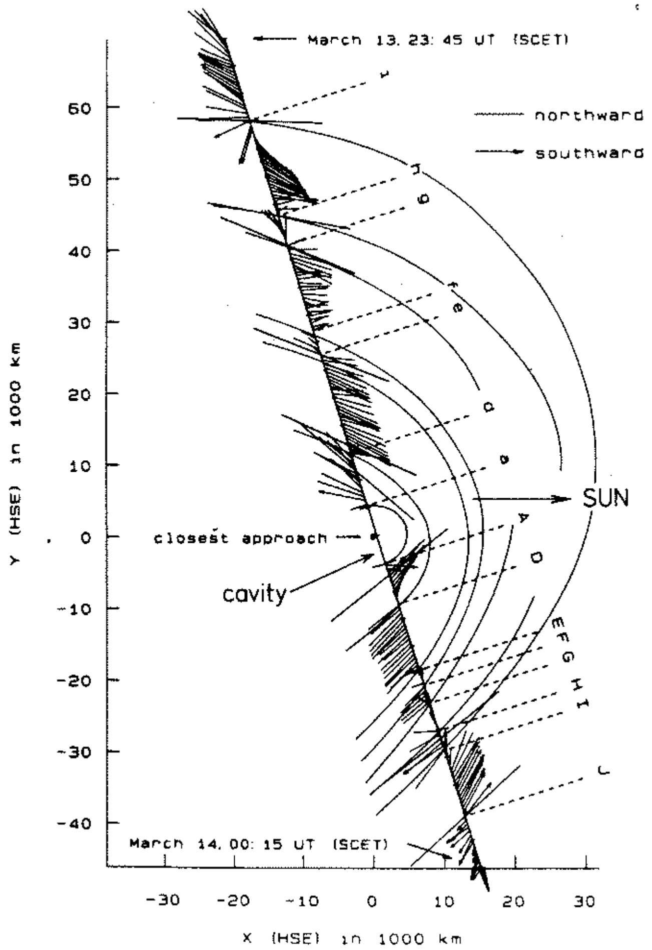

Fig. 3. Section of Fig. 2 from 23:45 UT March 13 to 00:15 UT March 14. The 4 s averages are decimated by 2. The magnetic layers with different polarity are sketched here

acting as an obstacle. Thus the magnetic field, frozen into the plasma will be enhanced by compression of flux tubes and stretching of field lines. Convected structures of the IMF will for the same reason be compressed when entering the pile-up region. These compressed IMF structures, namely the sheets seen by Giotto, will then move slowly through the pile-up region until they slip over the field free cavity and are accelerated into the ion tail. The vicinity to the heliospheric current sheet suggests that we are seeing part of the cascade of strong directional changes which sometimes are associated with the sector boundaries (Behannon et al., 1981).

It should be noted here, that Vega observations show a similar structure around closest approach, but with only one field reversal on either side of the nucleus (Riedler et al, 1986). The authors suggest, besides our interpretation above, that these discontinuities may be related to a diffuse layer related to the contact surface (ionopause), because the normal vectors of the discontinuities roughly point to the nucleus. Because the layers seen by Giotto extend to greater distances and most of their normals do not point to the nucleus, we conclude, that these features are not directly related to the contact surface.

The observation of the rather surprising number of field reversals may have implications for the model of disconnection events (DE). It is assumed, that a DE is driven by the penetration of a sector boundary (field reversal) into the cometary magnetic barrier and enhanced reconnection (Brandt, 1982). The question then arises, why many layers with opposite polarity can coexist deep in the pile-up region. Further detailed and comparative studies will be necessary towards a better understanding.

4. Conclusion

During the Giotto flyby at P/Halley, magnetic field data reveal magnetic field draping very clearly along the outbound leg and particularly close to the comet.

Table 1. Characteristics of the discontinuities in Figs. 2 and 3

Time (SCET)		ϕ_N (°)	θ_N (°)	λ_2/λ_3 (–)	$\lvert B_Z\rvert/B$ (–)	ω (°)	Label
86:03:13:	23:25:00	–	–	–	–	150	–
	23:30:00	84	−3	13	0.051	32	k
	23:38:19	–	–	–	–	98	j
	23:47:42.5	83	−33	42	0.057	155	i
	23:51:25	77	0	78	0.146	144	h
	23:52:28.5	69	−11	139	0.121	96	g
	23:53:20	76	−11	50	0.103	35	–
	23:55:36	−88	4	26	0.003	33	f
	23:56:23	86	−3	95	0.066		–
	23:56:27	81	−8	37	0.094	94	e
	23:57:32.5	55	−17	19	0.070	35	–
	23:59:42	64	−16	55	0.031	38	d
86:03:14:	00:00:40	56	−15	40	0.101	53	–
	00:04:04	−54	−5	271	0.338	107	–
	00:04:10	−56	18	112	0.177	117	–
	00:04:24	−49	0	26	0.048	60	–
	00:04:28	−42	8	107	0.014	35	–
	00:05:30	–	–	–	–	57	D
	00:08:02	−69	6	189	0.014	20	E
	00:09:03	–	–	–	–	44	G
	00:10:01	–	–	–	–	30	H
	00:10:19	−64	0	128	0.198	54	–
	00:10:44	−29	9	34	0.034	126	I
	00:13:13	−41	−8	63	0.107	95	J
	00:20:43	−26	−10	55	0.218	30	L
	00:22:26	−24	4	28	0.016	52	–
	00:29:00	−27	−4	358	0.097	46	M

Notes: ϕ_N is the longitude of the normal vector ($\phi_N = 0$ means sunwards), θ_N is the latitude. λ_2/λ_3 is the ratio of the intermediate to the least eigenvalue of the covariance matrix, $\lvert B_Z\rvert/B$ is the ratio of the absolute value of the magnetic field component in the normal direction to the mean magnitude

Inside the pile-up region the field consists of layers of opposite polarity, which arise from convected IMF structures.

Field reversals, convected into the pile-up region are not destroyed by diffusional effects or field line merging but persist even close to the ionopause.

The coexistence of adjacent sheets with opposite polarity close to the comet make a causal relationship between IMF polarity changes and disconnection events questionable.

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