

VARIABILITY OF COMET HALLEY'S COMA:
VEGA-1 AND VEGA-2 MAGNETIC FIELD OBSERVATIONS

K. Schwingenschuh	J.L. Phillips	J.A. Fedder	A.Somogyi	Ye. Yeroshenko
W. Riedler	J.G. Luhmann			
H.I.M. Lichtenegger	C.T. Russell			
Space Research Inst. Inffeldgasse 12 A-8010 Graz, Austria	Institute of Geophysics and Planetary Physics UCLA, CA 90024, USA	Naval Research Lab. Washington, DC 20375 USA	Central Research Inst. for Physics Budapest, Hungary	IZMIRAN, 142092 Troitsk, USSR

ABSTRACT

The differences of the VEGA-1 and VEGA-2 magnetic field investigations near comet Halley are discussed. The different draping structures of the magnetic field observed by VEGA-1 and VEGA-2 are caused by variations of the solar wind parameters and of the cometary activity during this period. The magnetic field reversal region observed only during the closest approach of VEGA-1 is correlated with high energetic particle streams and ground-based observations of a Disconnection Event (DE). A broad minimum of the wave activity during the inbound phase of both encounters occurs in the same region where a substantial change of the slope of the total magnetic field and of the plasma velocity takes place and where the observed neutral gas density has a discontinuity. The VEGA-1/2 magnetic field observations are compared with the results of 3-D MHD computer simulations.

Keywords: VEGA magnetic field observation, variability of comets, convected IMF, plasma boundaries at comet Halley.

1. INTRODUCTION

On March 6, 1986 at 7:20:06 UT the VEGA-1 spacecraft passed comet Halley at a distance of 8890 km on the sunward side of the nucleus. Three days later on March 9, 1986 VEGA-2 encountered the comet with closest approach at 8030 km (7:20:00 UT). The magnetic field experiment on both spacecraft observed a gradually increasing magnetic field magnitude during the inbound phase of the encounters (Ref. 1). The slope of the decreasing magnitude during the VEGA-1 outbound phase is higher than during the inbound phase. This asymmetry was most probably caused by the flyby geometry of the spacecraft. The angle between the sun - comet line and the spacecraft trajectory was about 111 deg. Due to a sensor failure at closest approach only the radial (approx. parallel to the sun - comet line) magnetic field component was observed on the outbound leg of the VEGA-2 flyby. The VEGA magnetic field investigators have already published some results describing boundaries (Ref. 3), convected IMF-features (Ref. 4) and fine structures in the cometary coma (Ref. 2). The purpose of this paper is to describe the main differences between the VEGA-1 and VEGA-2 magnetic field observations with a major emphasis on the region near the closest approach and to interpret these experimental data using the results of computer experiments (Ref. 5).

2. COMPUTER EXPERIMENTS

The computer experiments performed for these investigations are based on the numerical solution in three dimensions of the ideal, one fluid MHD-equations with mass loading terms included (in gaussian units):

$$\partial\rho/\partial t + \nabla \cdot (\rho \underline{v}) = A \quad (1)$$

$$\begin{aligned} \partial \underline{v} / \partial t + (\underline{v} \cdot \nabla) \underline{v} = \\ = - 1/\rho \{ \nabla(P + \eta) + \underline{B} \times \underline{J}/c \} - A \underline{v} / \rho \end{aligned} \quad (2)$$

$$\begin{aligned} \partial P / \partial t = - \nabla \cdot (P \underline{v}) - (\gamma - 1)(P + \eta) \nabla \cdot \underline{v} + \\ + \{ (\gamma - 1)/2 \} A v^2 \end{aligned} \quad (3)$$

$$\partial \underline{B} / \partial t = - c \nabla \times \underline{E} \quad (4)$$

$$\nabla \times \underline{B} = 4\pi \underline{J} / c \quad (5)$$

$$\underline{E} + \underline{v} \times \underline{B} / c = 0 \quad (6)$$

Here, ρ denotes the mass density, \underline{v} is the plasma flow velocity, P is the plasma pressure, \underline{E} and \underline{B} are the electric field and the magnetic induction, respectively, \underline{J} is the electric current density and A is the plasma production rate of the comet. Finally, c is the speed of light, γ is the ratio of specific heats and η is an artificial viscosity which must be taken into account for numerical purposes. The discretization of the above equations is performed on a 3-dimensional cartesian non-uniform grid containing $33 \times 29 \times 29$ gridpoints and extending 2.4×10^6 km upstream and 7.2×10^6 km downstream from the nucleus as well as $\pm 1.2 \times 10^6$ km in the two perpendicular directions. The (spherically symmetric) cometary plasma production rate is assumed to depend on the distance R from the nucleus as

$$A = mQ\sigma / (4\pi R^2) \exp\{-\sigma R/w\} \quad (7)$$

where m is the mean molecular mass of the cometary

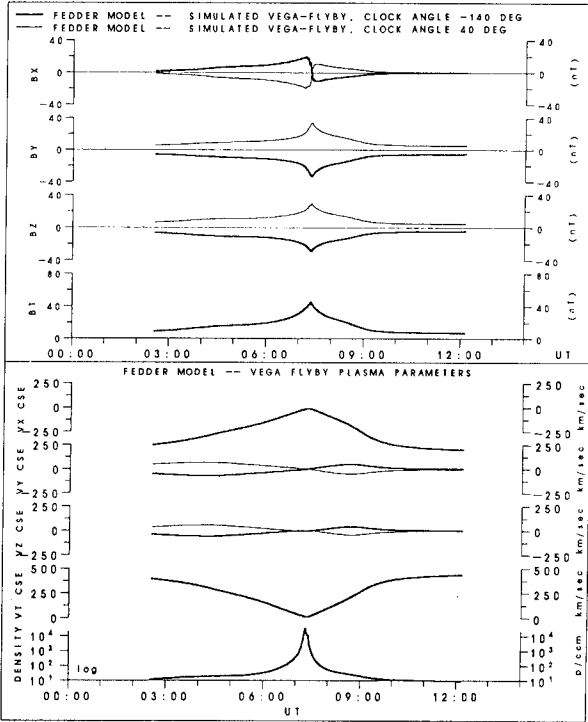


Fig. 1: The upper 4 panels show the simulated magnetic field components and magnitude, the lower 5 panels the simulated plasma velocity and density. These numerical simulations along the VEGA trajectory used a constant clock angle of -140° (heavy line) and 40° (light line) respectively.

particles, Q is the number of particles per second produced by the comet, σ is the ionization rate and w is the expansion velocity. The equations (1) - (6) were solved for several different initial values of the solar wind parameters; they are summarized in Tab.1. In equ. (7) a mean molecular mass of 20 AMU, an expansion velocity of 1 km/sec and an ionization rate of 10^{-6} per second was used throughout. At the beginning of the computation the IMF points perpendicular to the solar wind flow, i.e. perpendicular to the sun-comet line and is aligned with the z-axis of the simulation grid. The computation is stopped when a quasi steady state is obtained throughout the simulation mesh. The simulations were carried out using a steady initial IMF. This disadvantage can be compensated for up to a certain degree if one uses the preservation of the "clock-angle" ($\theta = \arctan(B_z/B_y)$) while the fieldlines approach the comet (Ref. 11). The observed clock angle can then be used to simulate different IMF directions by continually rotating the trajectory about the angle θ around the sun-comet axis.

Fig. 1 shows magnetic field and plasma data obtained by two simulated flybys along the VEGA trajectory using one of Fedder's MHD models (simulation "NORM"). The first flyby (dark traces) used a clock angle of -140° which is close to the average VEGA-2 inbound clock angle. Typical for this simulated flyby is the changing of the BX polarity from plus to minus near closest approach. For the second flyby (light traces) a clock angle of $+40^\circ$ was used. This angle is similar to the one observed inbound by VEGA-1. The deceleration of the total solar wind velocity can be seen on the

Name of Simulation	$n(\text{cm}^{-3})$	$V(\text{km/sec})$	$B(\text{nT})$	$Q(10^{30}/\text{sec})$
VEGA	9	450	7	1.3
SLOW	12	330	7	0.6
NORM	9	450	7	0.6
FAST	4	700	7	0.6

Table 1: Parameters of the computer simulations: n , V and B are the density, velocity and perpendicular IMF of the undisturbed solar wind. The gas production rates Q used were $1.3 \cdot 10^{30}/\text{sec}$ (simulation "VEGA") which is close to the value observed by VEGA (Ref. 12) and $0.6 \cdot 10^{30}/\text{sec}$.

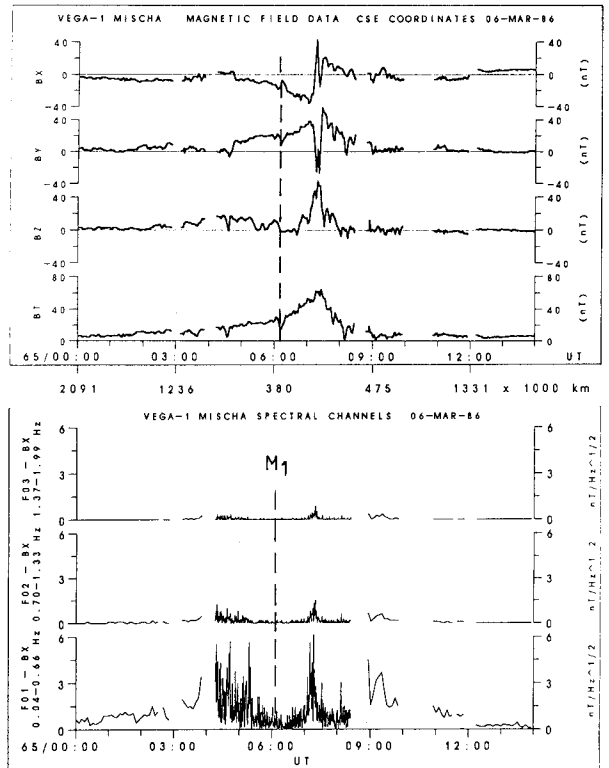


Fig. 2: VEGA-1 magnetic field observations during the Halley encounter. The lower panels show three spectral channels of the VEGA-1 magnetometer in the frequency range 0.04 to 2 Hz (BX-component). Note the multiple field reversals of BX near closest approach and the discontinuity of the total magnetic field slope at 6:10 UT. This M1 boundary has a distance to the nucleus of about 330 000 km.

lower panels of Fig. 1. Near closest approach the plasma velocity becomes smaller than the flyby velocity and the spacecraft can therefore overtake plasma parcels which were passed in the outer part of the trajectory. Thus the spacecraft is moving backward in the time history of the solar wind. Due to the low solar wind velocity near closest approach IMF features from different regions of the solar wind can form layered magnetic field structures (Ref. 4). This was observed during the VEGA-1 encounter.

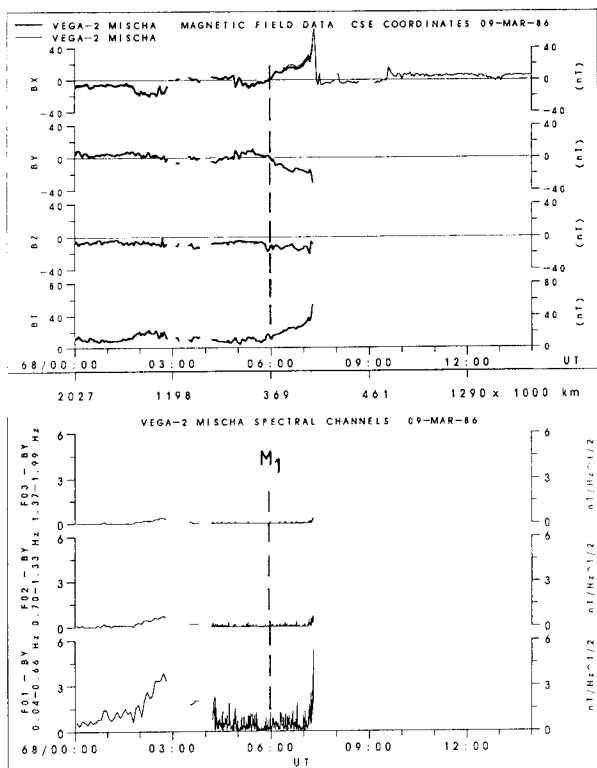


Fig. 3: Magnetic field components, magnitude and BY-spectra observed during the VEGA-2 encounter of Halley. The data gap of BY, BZ and BT after the closest approach is due to the failure of the main magnetometer sensor at 7:18 UT. The M1 boundary was encountered at a distance of 370 000 km.

3. OBSERVATIONS

3.1 Quasi-stationary structures in the inner coma

The magnetic field observations of both VEGA encounters are mainly characterized by the slowly increasing field magnitude during the inbound phase and by the reversal of the radial BX component near closest approach (Fig. 2 and Fig. 3). The radial magnetic field component observed by VEGA-1 shows a negative to positive polarity change during closest approach. In contrast to VEGA-1, VEGA-2 observed a positive BX before and a negative BX after the encounter. The magnetic field experiments on both spacecraft detected a sudden increase of the slope of B-total during the inbound phase of the Halley encounters. This M1 boundary (Ref. 3) was observed by the magnetic field experiment aboard VEGA-1 and VEGA-2 at a distance of 330 000 km (VEGA-1) and 370 000 km (VEGA-2), respectively. A magnetic field depression with a length of about 20 000 km is separating the two regions with different slopes. The M1 boundary is also associated with a broad minimum of wave activity in the frequency range 250 - 750 Hz observed by the low-frequency plasma wave experiment APV-N on board of both VEGA spacecraft (Ref. 6). A similar minimum was also observed in the lower frequency channels (0.04 Hz - 1.3 Hz) of the VEGA magnetometers (see Fig. 2 and Fig. 3). At the M1 boundary the population of the solar wind protons becomes comparable to the cometary ions (Ref.7) and the velocity of the plasma starts to decrease more rapidly (see Fig.4).

In the same region the neutral gas density observed by PLASMAG-1 on board VEGA-1 and VEGA-2 also shows a discontinuity (Ref. 12). The M1 boundary observed during the VEGA-1 encounter (Fig. 2) was about 40 000 km closer to the nucleus than the same boundary observed by VEGA-2 (Fig. 3).

3.2 VEGA observations of time-varying structures near the closest approach

The most striking feature of the VEGA-1 magnetic field observations near the closest approach (see Fig. 2) is the field reversal region, where the BX-component changes 3 times the polarity. During the VEGA-2 encounter only one polarity change was observed (see Fig. 3) near closest approach. This classical VEGA-2 draping pattern was already reproduced by computer simulations using a constant initial IMF before the cometary encounters (see Fig. 1). The VEGA-1 field reversals occur in a region 15 min before (70 000 km) and 5 minutes (23 000 km) after the encounter. The energetic particle instrument on board VEGA-1 detected inside this region an increased flux of particles (see Fig. 5). About 1 day after the VEGA-1 encounter a minor disconnection event was observed (Ref. 9).

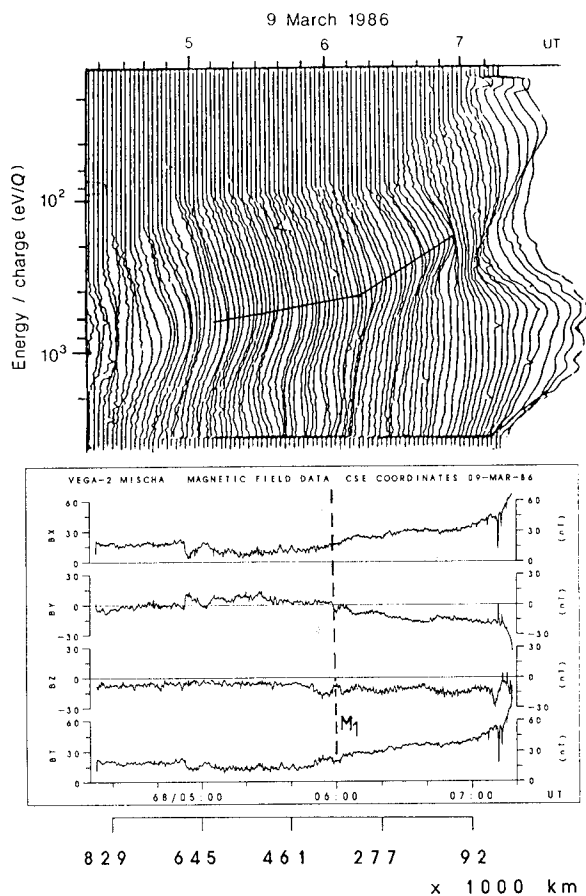


Fig. 4: Comparison between VEGA-2 magnetic field and plasma data (Ref. 7). Note that the change in the gradient of the plasma velocity occurs at the M1 boundary.

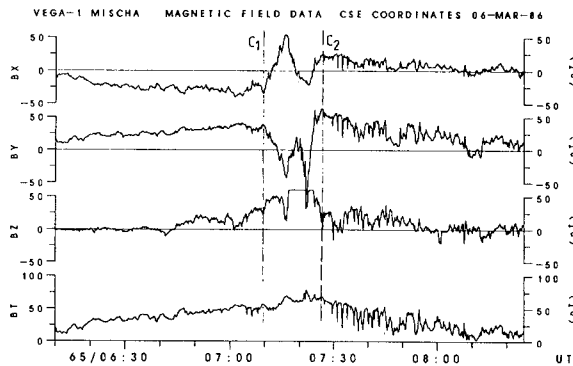
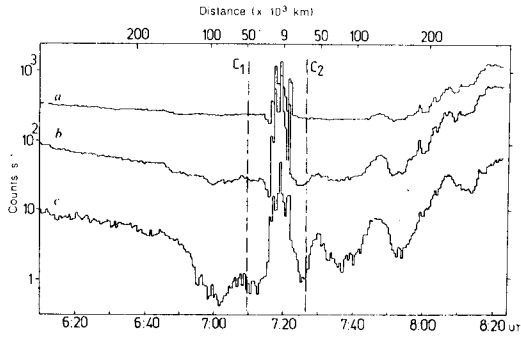


Fig. 5: VEGA-1 high energetic particle data in the range 40 - 60 keV (Ref. 8) and magnetic field data near the closest approach. The intensity spikes of the particles occur inside the field reversal region C1 - C2.

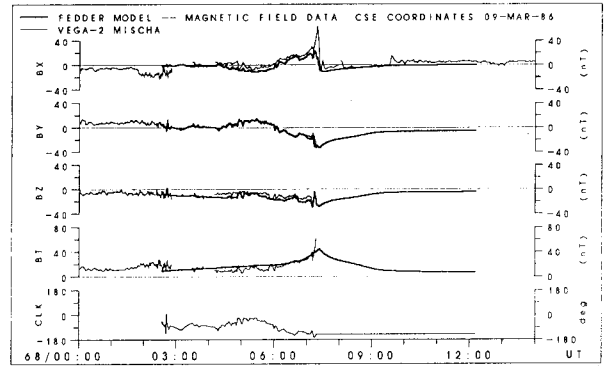


Fig. 7: Same comparison as in Fig. 6, but with VEGA-2 data. The clock angle used for the simulations after the encounter is an average value of the last vectors measured.

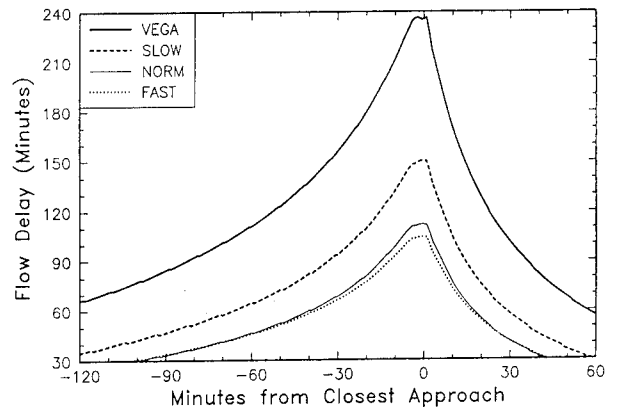


Fig. 8: Difference in propagation time between the unperturbed and the massloaded solar wind along the VEGA trajectory for different computer simulations (Parameters see Table 1).

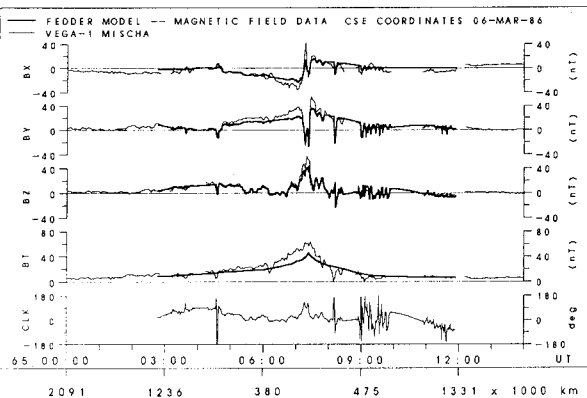


Fig. 6: Comparison of VEGA-1 magnetic field observations (light line) with numerical simulations (heavy line). The spacecraft trajectory is continuously rotated about the measured clock angle (lower panel) to count for the changes in the IMF direction. Note the good reproduction of the observed BX variations by the simulation indicating that most of the variability is caused by IMF structures and is not of cometary origin.

4. DISCUSSION

Most of the draping and compression of the IMF around the cometary obstacle is quite well reproduced by computer experiments using Fedder's 3-D MHD model. Fig. 6 and Fig. 7 show the comparisons between experimental and simulated magnetic field data. The simulations used the measured clock angle, shown on the lowest panels

of Figs. 6 and 7, as input and produced most of the magnetic structures. This indicates that most of the observed structures can be explained by IMF variations and are not caused by the variation of cometary parameters. The success of this limited model with no initial radial field component and only one ion species indicates that fluid effects are dominant in the observed region. One of the magnetic field features, which is not reproduced by these simulations is the discontinuity of the total magnetic field slope (M1 boundary). This boundary (see Fig. 2 and Fig. 3) was most probably caused by an increased massloading of the solar wind in the same region. In the Fedder model a spherically symmetric cometary production rate A with a radial dependence described in equ. 7 is assumed. A deviation of the neutral gas density from this simple formula was observed by both VEGA spacecraft (Ref. 12). Fig. 4 shows that the discontinuity in the plasma velocity gradient (Ref. 7) observed by VEGA-2 is well correlated with the M1 boundary observed by the VEGA magnetometers. The position of the M1 boundary did not show a substantial variation between the VEGA-1 and the VEGA-2 encounters, only the slope observed by VEGA-2 (see Fig. 3) before the M1 boundary was smaller than during the VEGA-1 encounter (see Fig. 2). The upstream solar wind velocity changed from 510 km/sec during the VEGA-1 flyby to 620 km/sec during the VEGA-2 flyby (Ref. 7) and the gas

production rate was higher during the VEGA-1 encounter (Ref.10). A boundary at the same position was not observed by the magnetometer on board Giotto, which passed Halley on March 14, 1986 00:03 UT (Ref. 13). This indicates that the M1 boundary has only a lifetime of several days and can therefore be regarded as a quasi-stationary feature of Halley's inner coma.

It was already proposed that the region with a layered magnetic structure observed by VEGA-1 at the closest approach is the result of convected IMF features (Ref.4). Due to this hypothesis VEGA-1 re-encountered a region of magnetization which has previously been encountered in the solar wind and slowed by mass loading to a speed below the spacecraft velocity of 79 km/sec. Computer simulations reveal that the time delay between outer and inner parts of the trajectory is mainly dependent on the outgassing rate and on the solar wind velocity. Fig. 8 shows this time delay for different simulation parameters. One can see that the delay increases with increasing outgassing rate (compare time delay of models NORM and VEGA in Fig. 8) and decreases with increasing solar wind velocities (models SLOW and FAST in Fig. 8). The solar wind velocity during the VEGA-2 (620 km/sec) encounter was higher than during the VEGA-1 flyby (510 km/sec) (Ref. 7), but the outgassing rate was smaller during the VEGA-2 encounter as determined by ground based observations (Ref. 10). Both facts are causing a smaller time delay during the VEGA-2 encounter. The chance to pass the same plasma parcel twice during the encounter is therefore much smaller for the VEGA-2 flyby. This may be a reason for the lack of convective IMF features during the VEGA-2 encounter.

The large delay time during the VEGA-1 encounter and the magnetic field layers with opposite polarity could have triggered a Disconnection Event (DE) observed about one day after the flyby (Ref. 9). The bursts of hot ions observed by the TUNDE experiment aboard VEGA-1 occur inside the field reversal region (see Fig. 5) and might be a signature of reconnection, which is causing the DE at the next day.

5. CONCLUSIONS

Based on comparisons between VEGA-1/2 magnetic field observations and MHD computer simulations it can be concluded that most of the measured variability is the result of IMF variations. The differences in the magnetic field structures observed near the closest approach of VEGA-1 and VEGA-2 were also influenced by the different solar wind velocity and cometary gas production rate. The discontinuity of the slope of the total magnetic field (M1 boundary) observed at distances of 330 000 km and 370 000 km during both VEGA encounters was not detected during the GIOTTO flyby. The M1 boundary can therefore be regarded as a quasi-stationary structure of comet Halley's inner coma with a lifetime of at least several days.

6. REFERENCES

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