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MAGNETIC FIELD DRAPING IN THE COMET HALLEY COMA: COMPARISON OF VEGA OBSERVATIONS WITH COMPUTER SIMULATIONS

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Abstract. During the VEGA-1 encounter with comet Halley, the magnetometer observed draping and compression of the interplanetary magnetic field (IMF). These are reproduced well by a 3-D MHD simulation of the cometary interaction. Rotations in the magnetic field similar to those at closest approach are also observed 2.75 hours earlier. We suggest that both rotations correspond to the same IMF interval and that the spacecraft had overtaken the plasma and encountered "older" magnetic field as it penetrated the coma. Analysis of the MHD model indicates that it should take ~ 3 to 5 hours for a solar wind parcel to pass from the unperturbed solar wind to VEGA-1 at closest approach. A simulated magnetic field profile composed of nested sections for different IMF orientations closely resembles the observations. This result supports the hypothesis of layered magnetic orientations in the coma.

Introduction

The VEGA-1 spacecraft encountered comet Halley on 6 March 1986, with closest approach (CA) at 8890 km on the sunward side of the nucleus (Sagdeev et al., 1986). The onboard magnetometer experiment (Riedler et al., 1986a) observed gradually increasing field magnitude during the inbound phase of the flyby and a faster decrease in magnetic field outbound. The radial field changed from anti-sunward to sunward during the encounter (Riedler, 1986b). These features are due to mass-loading of the solar plasma by cometary ions and resultant compression and draping of the field.

Analysis of the VEGA-1 observations near CA (Schwingenschuh et al., 1986) revealed more magnetic structure than a simple draping model (e.g., Alfven, 1957) would predict. An explanation of this structure is that it corresponds to the varying orientation of the interplanetary magnetic field (IMF) as the solar wind magnetized the cometary plasma. Since the velocity of the spacecraft in the cometary frame was over 70 km/s and the velocity of the plasma near the nucleus is much less than this, it is possible for the spacecraft to overtake the plasma that was magnetized earlier and in a sense reverse time. This can be tested by flying through an MHD model with varying IMF orientation to see if the observed field features can be reproduced.

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Observations

Low resolution VEGA-1 magnetometer observations are shown in Figure 1; the coordinate system is Cometocentric Solar Ecliptic (CSE), in which X is sunward in the ecliptic plane, Z is ecliptic northward and Y completes the right-handed set. The radial component (BX) shows three magnetic field reversals and the "east-west" component (BY) shows four reversals, all occurring from 15 minutes prior (~70,000 km from the nucleus) to 5 minutes after (~23,000 km) CA. Analysis of the boundaries (Schwingenschuh et al., 1986) identified two discontinuities (C1 and C2 in Figure 1) separating regions of different draping. The normals to these discontinuities were roughly perpendicular to the surface expected for a cometary "magnetopause", i.e., a locus of equal time delays along streamlines from a planar surface upstream. The region outside C1 and C2 in Figure 1 shows the draping produced by the prevailing IMF, while the draping pattern between boundaries was attributed to a different IMF orientation.

Since the solar wind, with its imbedded magnetic field, is slowed by mass-loading and near the nucleus moves more slowly than the spacecraft, the magnetic field nearest CA could be a manifestation of an "older" IMF than that in the outer parts of the trajectory. Accordingly, if the IMF is spatially homogeneous on the scale of the wind interaction region, and if the time of travel between the undisturbed solar wind and CA is shorter than the time of travel for a mass-loaded solar wind parcel, one should re-encounter in the coma features seen earlier in the solar wind.

To first order, the mass pickup process slows the flow inversely as the impact parameter of the solar wind streamline from the nucleus.

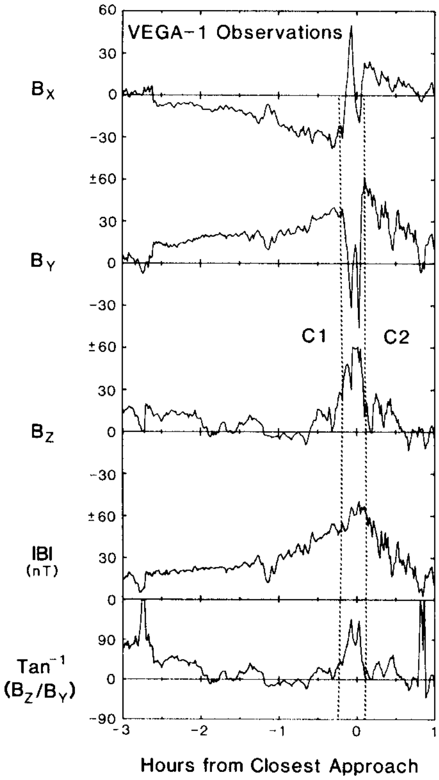

Fig. 1. Time series of 1-minute averaged VEGA-1 magnetometer data, in CSE, for period near CA. Bottom panel shows local clock angle, arctan(BZ/BY). Boundaries of discontinuities identified by Schwingenschuh et al. (1986) are labeled as C1 and C2.

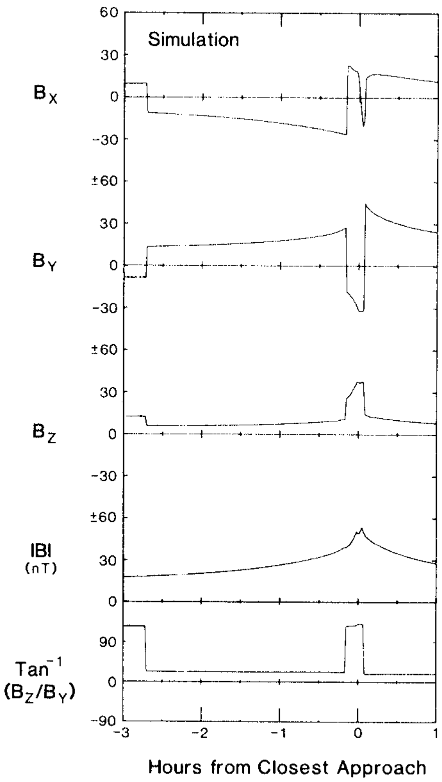

Fig. 2. Simulation corresponding to Fig. 1, using "VEGA" simulation parameters of Table 1. Two regions of different IMF orientation, based on observed orientation near CA, are obvious in clock angle plot (bottom panel).

The closer the asymptotic direction is to the nucleus, the greater the slowing. This piles up the flow and increases the magnetic field but does not twist the field lines much out of the plane defined by the upstream $\underline{B}$ and $\underline{V}$. Thus the angle of the cross-flow magnetic field is not much altered. Examination of the magnetic clock angle (arctan (BZ/BY), bottom panel of Figure 1), reveals a region of field direction similar to that at CA but observed prior to 2.7 hours earlier. This orientation and that at closest approach may correspond to the same solar wind epoch. Similar analysis of the clock angle as an IMF indicator was done by Schmidt et al. (1986). In the next section we use a numerical model to test the hypothesis that these two regions result from the same IMF event.

Numerical Simulation

The simulation used here was performed at Naval Research Laboratory, and is similar to a Giacobini-Zinner simulation described by Fedder et al. (1986). It uses a 3-D, single fluid MHD model incorporating mass, momentum, and energy source terms, and a non-uniform 33 x 29 x 29 rectangular grid extending 2.4 million km upstream and 7.6 million km downstream from the nucleus. The primary simulation run featured here uses a cometary production rate, based on the estimate by Gringauz et al. (1986), of 1.3 x 10^{30} neutrals/sec. Stewart (1987) estimated the production rate to be 1.4 x 10^{30} neutrals/sec, based on Pioneer Venus Orbiter ultraviolet spectrometer observations. Other simulation runs, performed prior to the VEGA encounters, used lower production rates; parameters are summarized in Table 1. All simulations used a molecular mass of 20 AMU, an ionization time of 10^6 sec, and a 1 km/sec outward neutral velocity. We have used the lower production rate models to test the sensitivity of the results to varying solar wind conditions.

Table 1. Simulation Run Parameters

Name of run	VEGA	SLOW	NORMAL	FAST
Production ($10^{30}s^{-1}$)	1.3	0.6	0.6	0.6
Solar Wind Velocity (km/s)	450	330	450	700
Solar Wind Density (cm^{-3})	9	12	9	4
IMF (nT)	7	7	7	7

If one assumes that the observed draped magnetic field lines are primarily parallel to the IMF $\underline{V}$-$\underline{B}$ plane, as is true in the model, the observations can be modeled by rotating the spacecraft trajectory to align the observed transverse field with the simulation IMF. Figure 2 shows a simulated time series that corresponds to the observations. This simulated flyby uses two different IMF directions, corresponding to the orientation of the IMF near the comet during CA and a second orientation present near the comet 2.7 hours before CA. Since as we shall see below the convected time for the solar wind deep into the coma is several hours, this second IMF

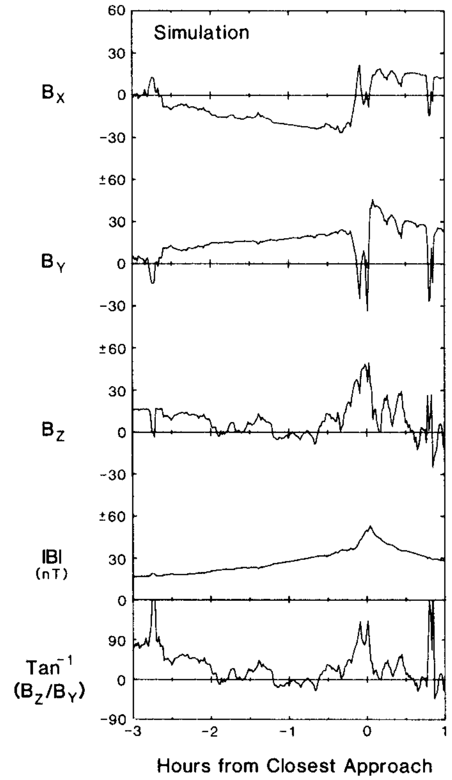

Fig. 3. Same as Fig. 2, except trajectory was rotated about the solar wind flow axis in order to match the simulation IMF direction with the cross-flow magnetic orientation for each 1-minute average.

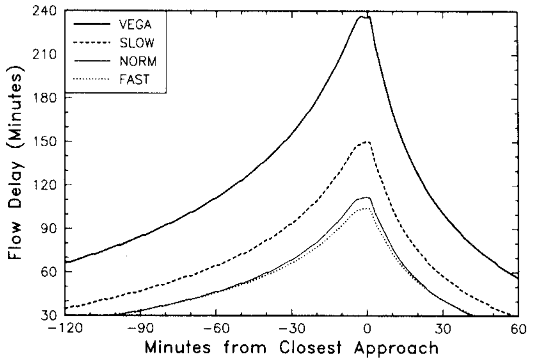

Fig. 5. Flow delay (propagation time minus unperturbed solar wind time) along VEGA-1 trajectory for each of four simulations of Table 1.

is used both for the time period prior to 2.7 hours before CA and for the period -9 to +4 minutes from CA. The similar orientation of these two fields is evident in the clock angle plot (lower panel) of Figure 1. In Figure 2 we have set them equal. The simulation field magnitude agrees well with the observations, although the peak magnitude is somewhat less (53 nT simulated, 70 nT observed). The simulation field components also match the observations, supporting the hypothesis that the observed field rotations near CA result from earlier IMF rotations.

By rotating the spacecraft trajectory about the solar wind flow axis such that the simulation IMF direction matches the locally observed Y-Z field direction for each measurement, one can better compare simulation and observation. This continual rocking of the simulation about the X-axis results in the time series of Figure 3. The similarity to the observations is striking in the field components, while the observed magnitude fluctuations are of course not duplicated in the simulation. It thus appears that much of the observed magnetic structure could result from variations in the cross-flow direction of the IMF. In Figure 2, we hypothesized that the field orientation seen at CA was a remnant field magnetized by the solar wind almost three hours earlier. Next we will quantify the storage capacity of the coma in terms of the time for propagation of magnetic features.

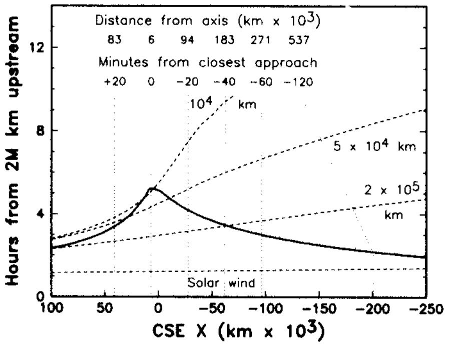

Fig. 4. Model flow propagation times, based on "VEGA" simulation parameters, showing propagation times from 2 million km upstream vs. distance along sun-comet axis. Heavy trace represents VEGA-1 trajectory. Dashed lines show unperturbed (450 km/s) solar wind propagation time and times for hypothetical spacecraft flying parallel to the sun-comet axis but displaced from this axis by the distances indicated for each line. Vertical dotted lines relate VEGA-1 X- position to time from CA and distance from the sun-comet axis.

Time Delays

To evaluate the above hypothesis, the simulation velocity was used to calculate the flow time, and hence the "age" of the draped magnetic field, throughout the coma. Integrating along simulation streamlines from the point of interest to the upstream limit of the velocity perturbation in the model (2 million km upstream) yields propagation times. Figure 4 is an overview of the model propagation times in the near-nucleus region. The heavy line shows propagation times along the VEGA-1 trajectory. The dashed lines show the characteristic times for spacecraft flying parallel to the sun-comet axis at various offset distances, and for the unperturbed solar wind at 450 km/s. The time for a fluid parcel to travel from 2 million km upstream of the nucleus to the spacecraft peaks near CA at just over 5 hours, compared to 1.2 hours for the undisturbed solar wind. Mass-loading thus appears to create ample flow delay to account for double observations of a single IMF region $2^1/2$ to 3 hours apart. Depending on the orientation of fronts of magnetic field direction in the solar wind, the apparent delay at VEGA-1 may be different. Furthermore, the time delay is sensitive to the streamline averaged mass loading rate, which may differ from the instantaneous rate at the encounter.

Since various solar wind and cometary parameters might affect the delay of solar plasma transiting the coma, three additional simulation runs, as described in Table 1, were used to determine the effects of cometary production rate and solar wind velocity. Figure 5 shows the difference in propagation time between the unperturbed solar wind and the mass-loaded solar wind for points along the VEGA-1 trajectory. Peak flow delays for a less active comet (neutral production rate of 6 x 10^{29} s^{-1}) range from 104 minutes for fast (700 km/s) solar wind to 149 minutes for slow (330 km/s) solar wind. This lower production rate is more appropriate for the Giotto encounter (Reinhard, 1986). For the active comet (1.3 x 10^{30} s^{-1}) the peak delay is nearly four hours. While the production rate for the VEGA enounters is uncertain, the range of simulation parameters used here probably approximate the encounter conditions. Thus it appears that by varying model parameters within a reasonable range one can reproduce the delay time in the observations.

Discussion and Conclusions

To first order the single fluid MHD model predicts the overall magnetic structure well. The field orientation seems well predicted; the peak magnitude is however somewhat underestimated. The predicted time delays are are also consistent with observations. The present model is restricted to field orientations normal to the solar wind flow, and uses only one ionization source (photoionization). A model incorporating additional factors would lead to improved prediction, but it is satisfying to see the success of the simple model.

The single fluid MHD model predicts sufficiently long flow delays that the reoriented magnetic field observed near CA can be explained in terms of earlier magnetization. Such layers can be pictured as nested shells of draped field with cross-flow orientations preserving a history of the solar wind over a few hours. The persistence of such layers has ramifications for cometary disconnection models (Niedner and Brandt, 1978; Russell et al., 1986). If the tail disconnection region is in front of the comet, disconnection will begin with a delay of at most a couple of hours; significantly longer delays after the arrival of a disturbance suggest that the triggering region is downstream.

Comparison of the various simulation runs indicates that the flow delay caused by mass loading varies directly with production rate and inversely with solar wind speed. For similar solar wind parameters, the peak flow delay along the VEGA-1 trajectory varies roughly linearly with production rate as can be seen by comparing the "Normal" and "Vega" models in Figure 5.

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