GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 6, PAGES 644-647, JUNE 1987

MIRROR INSTABILITY IN THE MAGNETOSPHERE OF COMET HALLEY

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Abstract. High resolution VEGA 1 and 2 magnetic measurements in the cometary magnetosphere and magnetosheath of Halley reveal the presence of fluctuations with the signature expected for the mirror instability. This instability is a mechanism by which homogeneously produced cometary ions with a large perpendicular temperature anisotropy can be concentrated into discrete linear features. Thus, the mirror instability may provide a new mechanism for the generation of cometary rays. To our knowledge the presence of this instability in the cometary plasma was not predicted.

Introduction

Visual observations of comets reveal that the cometary plasma is highly dynamic (cf. Brandt, 1982). However, it has been difficult to deduce the nature of the processes that cause the observed structure, solely from remote sensing. It is the purpose of this paper to use in-situ data from the VEGA spacecraft to determine what some of these mechanisms are.

On March 6, 1986, and again on March 9, 1986, VEGA spacecraft flew past the nucleus of comet Halley carrying a sophisticated array of field and plasma instrumentation. The magnetic field was recorded at a rate of up to 10 samples a second along the spacecraft trajectory by a fluxgate magnetometer supplied by the Space Research Institute, Graz, Austria (Riedler et al., 1986a). The initial results of this investigation have been reported by Riedler et al. (1986b) and Schwingenschuh et al. (1986) and Yeroshenko et al. (1986). Briefly, the VEGA-1 instrument functioned flawlessly through encounter, detecting the large-scale draped magnetic field configuration expected from MHD simulations (cf. Fedder et al., 1986), and possibly detecting a cometary bow shock both inbound and outbound. The VEGA-2 instrument also detected a large-scale draped magnetic field and a possible cometary bow shock inbound but a failure at closest approach left only a single axis measurement on the outbound leg.

The middle panel of Figure 1 shows one-minute averages of the magnetic field observed by VEGA-1. The features identified as possible inbound and outbound shocks (Galeev et al., 1986; Schwingenschuh et al., 1986) occurred just prior to and just after the region presented in this figure. The upper panel shows 2-second averages of the magnetic field in spacecraft coordinates observed outbound from closest approach in the interval from 0727 to 0743 UT. The lower panel shows the vector magnetic time series from 0753 to 0825 UT, immediately before the termination of the real-time transition. The former interval is characterized by steady fields slowly declining but punctuated by apparent diamagnetic depressions. The latter region is characterized by strong fluctuations in all the components with amplitudes exceeding that of the ambient background field. Similar amplitude waves were observed by the ICE spacecraft when it encountered comet Giacobini-Zinner (Smith et al., 1986). In this paper we examine the nature of the fluctuations seen near closest approach, identify their wave mode and infer the nature of their source.

Paper number 7L6531.
0094-8276/87/007L-6531$03.00

VEGA-1 Fluctuations

The average properties of the fluctuations seen in the upper panel of Figure 1 have been discussed by Yeroshenko et al. (1987). The depressions in field strength range in amplitude from 7 to 40 nT and last from 5 to 20 seconds. Assuming that the spacecraft velocity well exceeds any velocity of propagation or convection of these structures, these delays translate to dimensions of from 400 to 1600 km. A notable feature of these fluctuations is that they are separated by a distance greater than the thickness of the depressed field, i.e., by times of 60 to 150 seconds or 4000 to 10,000 km.

Figure 2 shows the full resolution, 10 samples per second, magnetic measurements across the apparent diamagnetic feature observed outbound at 0731 UT. The upper left-hand panel shows the vector time series in spacecraft oriented coordinates. There is a strong but rather smooth drop in the magnetic field strength and then a recovery. The lower left-hand panel shows the same data rotated into the minimum variance coordinate system. On the right are shown hodograms of the field variation in this minimum variance coordinate system. The top panel shows the plane of maximum variation. The lower panel shows an orthogonal plane. The variation in the magnetic field through the feature is quite linear but it is not parallel to the background magnetic field. If it were parallel, the field change would radiate from the origin of the hodogram. The small uncertainty in the zero levels of the readings (about 2 nT) does not account for the apparent orientation of the field variation.

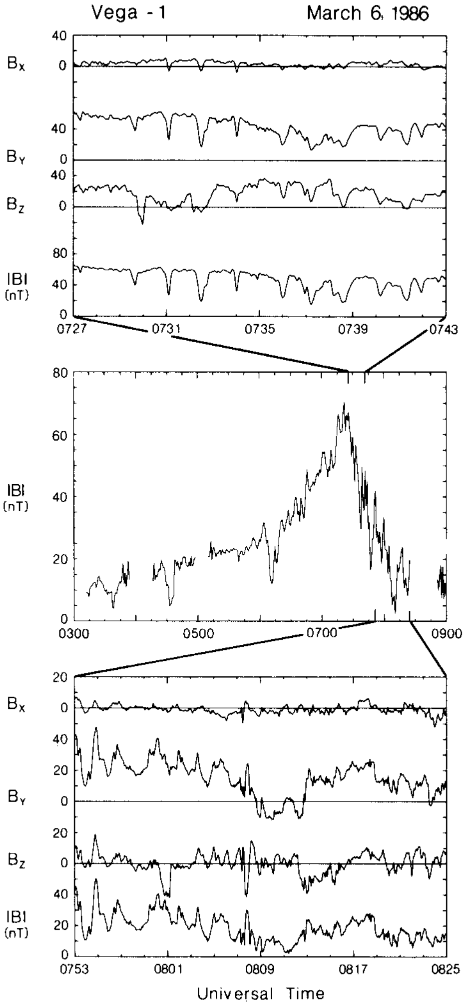

Fig. 1. One minute averages of the magnetic strength observed by VEGA-1 on its passage by Halley on March 6, 1986 are shown in the middle panel. The upper panel shows 2-second resolution vector measurements (4-second averages overlapped by 2 seconds) in the spacecraft coordinate system from 0726 to 0742 UT. The lower panel shows 2-second resolution vector magnetic measurements from 0752 to 0824 UT.

An MHD slow wave could have such a magnetic variation if it were propagating at an angle to the magnetic field. If a slow wave attempts to propagate exactly perpendicular to the magnetic field, it has zero propagation velocity and forms a tangential discontinuity or equivalently an entropy fluctuation that would have a 'radial' hodogram signature pointing toward the origin (cf. Kantrowitz and Petschek, 1966). However, this is clearly not the case here. This suggests that the wave is propagating at an oblique angle to the field. Fast and slow waves have magnetic perturbations which are perpendicular to the direction of propagation and which lie in the plane containing the background magnetic field and the propagation vector. This behavior allows us to find the direction of propagation by noting that the vector cross product of the background magnetic field and the change in field is perpendicular to the propagation direction as is the change in field itself. Thus the triple vector cross product of first the field change and the background field and then the field change is parallel to the propagation direction. We note that this formula is effectively the usual "magnetic coplanarity" normal but is less sensitive to zero level errors because it does not depend on knowing the exact orientation of the field at the minimum of the slow mode oscillation. Using this technique, we find that this wave is propagating at an angle of 67.5° to the background magnetic field.

Analyses of the other events yield similar results with angles of propagation from 67.5° to 80°, the larger angles occurring farther from the nucleus.

VEGA-2 Fluctuations

As mentioned above, only one-axis measurements are available from VEGA-2 after closest approach so that an analysis of fluctuations in the corresponding portion of the VEGA-2 trajectory is not possible. However, a pair of these waves were detected inbound on the VEGA-2 encounter in contrast to the VEGA-1 pass in which no such fluctuations were seen inbound. The first and strongest of these fluctuations is shown in Figure 3 at 0711 UT. This wave is propagating at an angle of 64° to the magnetic field. Two minutes later a similar but weaker fluctuation was observed propagating at 65° to the magnetic field.

At both these times enhancements in the heavy ion density by almost a factor of 2 were

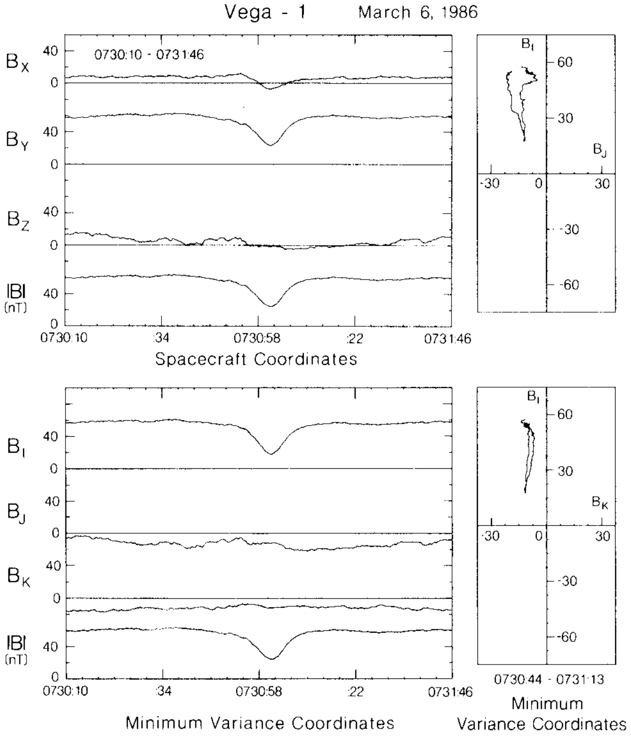

Fig. 2. Full resolution, 10 sample per second, VEGA-1 vector magnetic measurements from 0729:15 to 0730:15 UT at a distance of 45,000 km from the nucleus. The upper left-hand panel shows the time series in spacecraft coordinates, with the x-direction approximately toward the sun and the z-direction along the ecliptic pole. The lower left-hand panel shows the time series in minimum variance coordinates. The right-hand panels show hodograms of the variations of the field from 0729:49 to 0730:18 UT in two orthogonal planes.

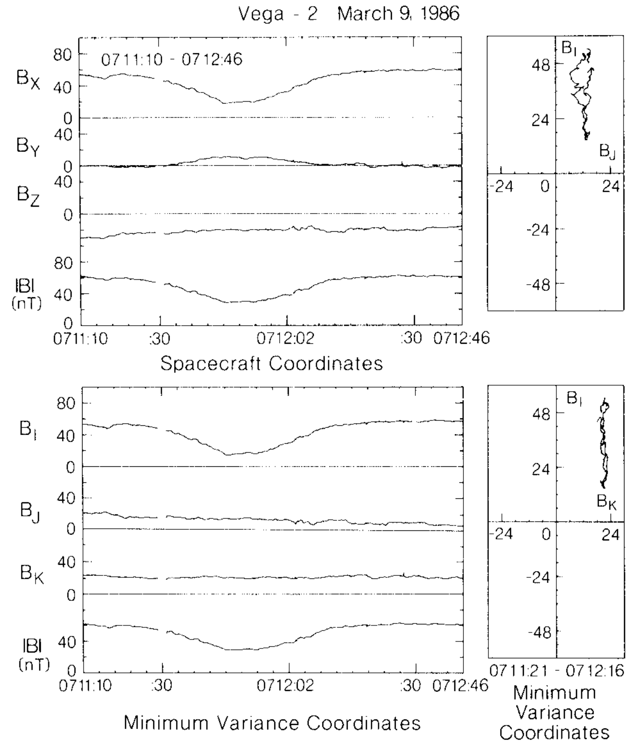

Fig. 3. Full resolution vector measurements from VEGA-2 over the interval 0711:10 to 0712:42 UT on March 9, 1986 at a distance of 40,000 km from the nucleus. The right-hand panels cover the interval from 0711:21 - 0712:16 UT.

observed by the PLASMAG-1 detector (Galeev et al., 1986b; Gringauz et al., 1986). Galeev et al. (1986b) and Klimov et al. (1986) have interpreted these enhancements in terms of the critical ionization velocity effect (Alfven, 1954) in part because of the presence of plasma waves in these enhancements. However, it is quite possible that plasma waves could be stimulated by the passage of other waves too.

Similar observations have been reported to occur in the Earth's magnetosheath by both Crooker et al. (1977) and most recently by Moustaizis et al. (1986). In both these studies the plasma density was observed to be in antiphase with the magnetic field. Repeating the analysis above for such waves in the ISEE data shows very similar results with the waves propagating more nearly perpendicular to the field than the VEGA waves.

Discussion and Conclusions

The oscillations seen in the magnetic field just after closest approach on VEGA-1 and just before on VEGA-2 have some of the properties of the MHD slow mode. They are linearly polarized and the VEGA-2 data show that the magnetic depression is anticorrelated with a density enhancement. Similar waves are observed in the terrestrial magnetosheath. These waves are also accompanied by plasma waves in the density enhancements as are the VEGA waves. While the waves have the signature of MHD slow waves it is unlikely that they are an MHD phenomenon. The plasma is expected to be very anisotropic at the location in which the waves are observed and the apparent wavelengths are similar to the gyroradius of the heavy ions. The waves are seen closer to the nucleus than the cometopause (Gringauz et al., 1986) where the streaming solar wind ions have disappeared. Here the field is quiet except for the waves under discussion. The ion density should consist of ions picked up perpendicular to the magnetic field and hence the perpendicular ion temperature should be much greater than the parallel ion temperature. This anisotropy can drive the mirror instability which has a wave signature similar to that of the slow mode discussed above. The mirror mode is expected to be non-propagating. It also should have a wave normal at a large angle to the magnetic field, depending on conditions in the plasma (cf. Barnes, 1966). This is consistent with observations. If the mirror instability is dominant as it appears to be here and at least on occasion in the Earth's magnetosheath, (Crooker and Siscoe, 1977), it leads to a natural explanation of the field depression, the plasma enhancement and the plasma waves both in the VEGA data at Halley and in the Earth's magnetosheath.

For instability, the ratio of the perpendicular pressure to the parallel pressure must exceed unity by at least the reciprocal of the perpendicular beta of the plasma (Chandrasekhar et al., 1958; Vedenov and Sagdeev, 1958). However, the ion cyclotron instability which is also unstable when the perpendicular temperature exceeds the parallel temperature was expected to have a larger growth rate (Gary et al., 1976). A possible solution to this dilemma has been proposed by Price et al. (1986) who note that in a multicomponent plasma the dispersion relation is altered by the additional species. When the free energy for the instability resides in the lighter ion, the mirror growth rate will exceed the ion cyclotron. Hada (personal communication, 1987) have confirmed this result using a 2-dimensional simulation. In this region of the comet we expect that the dominant ion is the picked up H_2O ions and the next most dominant ion is CO. In fact at the time of the 0711 UT VEGA-2 oscillation, there were about 40 H_2O ions cm^{-3}, 20 CO ions cm^{-3} and 4 CO_2 ions cm $^{-3}$ (Gringauz et al., 1987).

These waves are quite different from those observed at larger distances and which appear to be fast magnetosonic waves (cf. Smith et al., 1986). At large distances there is a significant solar wind component streaming through the cometary ions. This ion/ion streaming configuration leads to right-hand polarized instabilities as described by Winske et al. (1985) and Winske and Gary (1986). Close to the comet inside the cometopause (Gringauz et al., 1986), the solar wind ions do not penetrate and the plasma is dominated by picked-up ions whose energy is almost totally perpendicular to the magnetic field. This anisotropy should be unstable to the mirror mode if the lighter ions contain the bulk of the free energy in the perpendicular temperature anisotropy (Hada, personal communication, 1987). Oblique wave normals are expected to arise from the mirror mode (Barnes, 1966). The variation of wave normal direction is probably a result of the varying ion composition and temperature anisotropy with cometocentric distance. The resulting ion condensations should be non-propagating and convected along with the fluid. They could resemble rays. Examples of the expected configuration of the magnetic field under such circumstances can be found in Figure 8 of Price et al. (1986) and Figure IV.2 of Siscoe (1983).

If the mirror instability is responsible for the growth of cometary rays, then the present paradigm that rays are field-aligned in the comet may be incorrect. The mirror instability will grow ion condensations at an angle to the magnetic field and the lengthening of the ray may reflect the spatial growth of the instability. We note a previous model has also associated a wave instability with ray growth (Baker et al., 1986). In this model the free energy was postulated to be a gradient in the plasma mass density and the unstable model to be the interchange instability.

In summary, these observations suggest a new possible mechanism for the generation of cometary rays. We can say nothing about the nature of the ionization process from these results. For example, the CIV process (Galeev et al., 1986) may play a role. However, once the ions are formed, it appears that, in the region within 10^5 km of the nucleus of Halley, the ions can concentrate themselves via the mirror instability, through the action of the cometary magnetic fields, into discrete ray-like structures.

Acknowledgments. The authors wish to acknowledge very helpful discussions of these results with A. Barnes, S. P. Gary and T. Hada. This research was supported at UCLA by the National Aeronautics and Space Adminstration under research grant NAGW-717, and at Graz by the Austrian Ministry of Science and Research.

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(Received March 23, 1987
accepted April 18, 1987.)