**Observation of magnetic flux ropes in the Venus ionosphere**

**Magnetic** field measurements made by the Pioneer Venus Orbiter spacecraft reveal a very low average field strength within the dayside ionosphere of Venus, typically only a few nanoteslas, in contrast to fields of several tens of nanoteslas just outside the ionosphere. Thus, at least in the range of solar zenith angles (65°–90°) initially probed by the orbiter, the compressed interplanetary magnetic field of the shocked solar wind plasma (the magnetosheath) is effectively shielded from the ionosphere by currents flowing on the ionopause, the boundary between the ionosphere and the magnetosheath. In addition, the magnetic field pressure just outside the ionopause approximately balances the ionospheric thermal plasma pressure. However, within this generally low-field region the spacecraft occasionally passes through regions of very large field strength which can sometimes exceed that observed external to the ionosphere. These intense, short-lived enhancements are described here and interpreted to be due to the passage of the spacecraft through 'flux ropes', bundles of twisted magnetic field lines surrounded by ionospheric plasma.

Figure 1 shows the magnetic field strength observed near periapsis on the third orbit of Pioneer Venus. The spacecraft moves from an altitude of 209 km and a solar zenith angle of 66.7° to an altitude of 332 km and an angle of 69° during this time. Numerous enhancements occur throughout the ionospheric passage, and the field components (not shown) undergo complicated variations within each enhancement. It is unlikely that these variations are purely temporal, as the spacecraft is travelling faster than plausible wave disturbances. For example, with local ionospheric densities $>10^3$ cm$^{-3}$, temperatures of roughly 2,000 K (refs 2, 3), and a background field of roughly 2 nT, the Alfven speed is $\sim 0.5$ km s$^{-1}$, while the sound speed is $\sim 1$ km s$^{-1}$. The orbital speed of the spacecraft near periapsis is $\sim 10$ km s$^{-1}$, so we are probably observing spatial structures. Because the spacecraft grazes these structures at various distances from their centres, the magnitude and duration of the enhancements are variable, as can be seen in Fig. 1. This figure also shows that structures often overlap one another, and for clarity, we have analysed only distinctly separate enhancements.

In an attempt to reduce the field variation to two dimensions, we have performed minimum variance analyses of some of these enhancements. Figure 2a shows the field variation, in the principal axis system, of the structure observed between 1432.37.3 and 1432.508 UT on orbit 3. The $i$, $j$, and $k$ components refer to the maximum, intermediate and minimum variance directions respectively. Figure 2b shows the results of a minimum variance analysis applied to a passage through a model field describable by the following equations:

$$B_x = B(r) \times \cos(\alpha(r))$$

$$B_y = B(r) \times \sin(\alpha(r))$$

where

$$B(r) = B_0 \times \exp(-\rho^2/l_0^2)$$

and

$$\alpha(r) = \pi/2 \times (1 - \exp(-\rho^2/l_\alpha^2))$$

These equations define a helical magnetic field, whose magnitude and pitch $\alpha$ depend on the radial distance $r$, from the axis of the structure. $B_x$ and $B_y$ are, respectively, the azimuthal and axial components of the field. The scale lengths $l_\alpha$ and $l_0$ determine how rapidly the pitch and magnitude vary with distance from the axis. For the case shown in Fig. 2a, $l_\alpha = 3.2$, $l_0 = 4.5$, and the distance of closest approach to the axis was 2.0.

**Fig. 1** Magnetic field enhancements observed within the ionosphere shortly after periapsis (at 1431.56) on orbit 3 of Pioneer Venus. Before and after this interval, the characteristic ionospheric field strength is less than 10 nT, while the peak field just outside the ionopause is $\sim 55$ nT.

**Fig. 2 a, b** Comparison of the magnetic structure of one of the enhancements shown in Fig. 1 (a), and a model of the enhancement (b), the coordinate system is the principal axis system given by minimum variance analysis, and the fields are in nanoteslas. The model parameters are discussed in the text. 15.5 s of data are shown. Hodograms of the structure (c) and the model (d). Orbit 3 of Pioneer Venus; 7 December 1978; 1432.37.3–1432.508; $l_\alpha = 3.2; l_0 = 4.5; \rho_{\text{min}} = 2$. 

Hodograms of both the observations and the model are shown in Fig. 2c, d; the field vector swings through a full 180° in the i-j plane, passing through maximum magnitude near 90°. The distinctive variation in $B_z$ is a result of passing through the helical structure off-axis.

The magnetic configuration suggested by the data and described explicitly by the model is shown in Fig. 3. Because of the helical nature of the magnetic field, the structure resembles a rope of twisted magnetic flux tubes: the magnetic field is axial and at its peak strength in the centre of the structure, becoming weaker and more azimuthal with increasing distance from the axis.

The currents which produce this helical magnetic structure are shown in Fig. 4a, b, both in the cylindrical coordinates of the structure and in coordinates parallel and transverse to the magnetic field at each point. Note that throughout the modelled passage the axial current is always dominant.

To determine the source and evolution of these flux ropes, we next examine their amplitude and occurrence frequency with altitude. Figure 4c, d shows these quantities combined for orbits 3, 4, 6 and 7. The altitude range is divided into 25-km bins, and the total number of flux rope structures per bin is shown in Fig. 4c. Because of its orbit, the spacecraft spends more time in the low-altitude bins than in the high, and this effect can be seen as an increase in total number of structures per bin with decreasing altitude. The altitude interval 150–175 km was sampled only during orbit 7, and does not have an observing time comparable to the higher altitude bins. To correct for the varying observing time with altitude we have determined the ratio of the total time spent within flux ropes to the total time spent within an altitude bin, as shown in Fig. 4c. There seems to be a slight increase in occurrence rate at lower altitudes. Additional data, especially when Pioneer Venus returns to the dayside ionosphere, will be needed to confirm this tendency.

If the magnetic field in these structures is in pressure balance with the surrounding ionospheric plasma, one would expect their characteristic field strength to increase with decreasing altitude, as the plasma thermal pressure increases. Figure 4d shows the peak flux rope amplitude observed within each altitude bin, and indeed, the amplitude seems to increase with decreasing altitude. The 150–175 km bin is the most notable exception to the trend, perhaps because this lowest altitude interval was sampled only on orbit 7. The right portion of Fig. 4d shows the median of the distribution of flux rope amplitudes within each bin. The distribution suggests that, at altitudes below 350 km, amplitudes increase overall with decreasing height, but results above 325 km have less statistical accuracy because of the small number of samples in those intervals.

Although the results shown are only based on four orbits of data they, nevertheless, carry implications for the source and evolution of flux ropes. First, the suggestion that these structures are more numerous at lower altitudes may be due to either a "piling up" effect or to a source at low altitudes. The former might occur if magnetosheath magnetic flux tubes were pulled into the ionosphere by solar wind convection, such as has been proposed for the terrestrial magnetopause. These structures would slow down and pter up in the denser, slower moving lower ionosphere. If, however, these structures result from a source in the lower ionosphere, they might percolate upwards due to buoyancy; indeed, the enhanced magnetic field pressure within these structures implies the reduction of the plasma thermal pressure there, and if this shows up as a reduction in ion/electron number density, flux ropes must be buoyant with respect to the sur-}

Fig. 4 a, b Current densities (arbitrary units) of the model structure in Fig. 2a, b. The cylindrical components (a) $J_y$ and (b) $J_z$ refer to the azimuthal and axial current contributions, while (c) $J_r$ and (d) $J_t$ are the contributions parallel and transverse, respectively, to the local magnetic field vector. The abscissa is distance along the spacecraft trajectory which in this case does not pass through the centre of the rope. Distributions of occurrence frequency (c) and amplitude (d) with altitude.

The surrounding plasma. A similar process is believed to occur in the terrestrial equatorial ionosphere. The helical nature of flux ropes could develop from velocity shear in the ionosphere, due perhaps to a viscous interaction with the magnetosheath at the ionopause. Given the observed ionospheric temperatures and densities, and flux rope scale diameters between 10 and 100 km, the magnetic diffusion time of such structures would be many hours. Thus flux ropes are likely to persist long enough to be transported, not only from the ionopause to the lowest ionospheric levels (or vice versa), but from the subsolar region to the terminator as well.

Whatever their source, these ionospheric flux ropes may play an important part in the solar wind–ionosphere interaction, and ionospheric plasma transport and heating. Analysis of the early Pioneer Venus data is continuing to define better the nature of this unexpected phenomenon.

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