MAGNETIC FLUX ROPES OF VENUS: A PARADIGM FOR HELICAL MAGNETIC STRUCTURES IN ASTROPHYSICAL SYSTEMS

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The magnetic flux ropes of Venus are small scale (ion gyroradius) cylindrically symmetric structures observed in situ by the Pioneer Venus orbiter in the largely magnetic field-free ionosphere of the planet. They are so named because of their helical magnetic structure, which in turn is due to primarily field-aligned currents within the rope. Empirical models can be used to examine the current structure in detail, and these models indicate that flux ropes may be unstable to the helical kink mode. Statistics of rope distribution and orientation also support this instability picture. The results of investigations into the direct measurements of Venus flux ropes may be relevant to certain astrophysical phenomena that must be observed remotely.

Flux ropes are basically tubes of magnetic flux; the field is strongest at the center where it is also purely axial in orientation. At greater distances from the axis, the field becomes weaker and more helical until at large distances it is very weak and almost entirely azimuthal. The structures envisioned here are cylindrically symmetric, in that if z is taken along the rope axis the field is

$$\underline{B}(\rho) = B_\phi(\rho)\,\hat{\phi} + B_z(\rho)\,\hat{z}$$

where ρ and ϕ correspond to the usual cylindrical coordinates. Such a structure automatically satisfies $\underline{\nabla} \cdot \underline{B} = 0$. The field components could be further described as $B_\phi(\rho) = B(\rho)\sin\alpha(\rho)$ and $B_z(\rho) = B(\rho)\cos\alpha(\rho)$ where $\alpha(\rho)$ is the helical pitch of the field, which satisfies the boundary conditions $\alpha(\rho) \to 0$ as $\rho \to 0$, and $\alpha(\rho) \to \pi/2$ as $\rho \to \infty$.

The magnetic field structure of flux ropes can be explicitly modeled for cases in which the spacecraft passed very close to the center of the rope. Elphic and Russell (1983a) have fit a model to magnetic field data, and took the curl of the model to obtain the current densities flowing locally parallel and perpendicular to the magnetic field, shown in Figure 1. In most cases, as here, field-aligned currents dominate the rope structure, suggesting that $\underline{J} \times \underline{B}$ forces are small and that ropes tend toward a force-free configuration.

Modeling the detailed magnetic structure of ropes allows us to evaluate their stability to pinch-related perturbations. For example, we may use the 'sausage' pinch (m = 0) instability or 'helical kink' (m = 1 or −1) instability criteria to evaluate the susceptibility of

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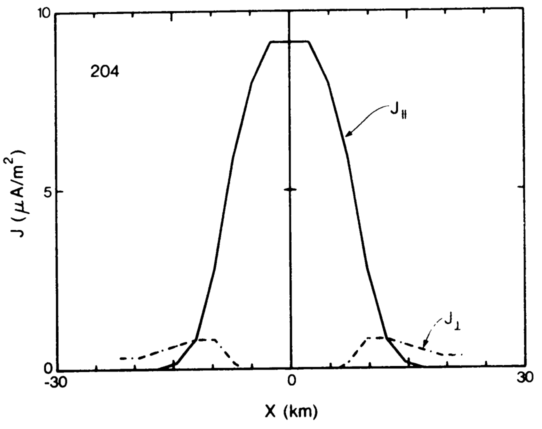

Figure 1. Current densities parallel and perpendicular to local magnetic field.

ropes to these modes. None of the flux ropes heretofore modeled even approach instability to the sausage pinch. The 'helical kink' however has a lower threshold for instability than the sausage pinch. If we approximate the flux rope magnetic field as $B_z = B_{z0}$, $B_\phi = 0$ for $0 < \rho < a$, and $B_z = 0$, $B_\phi = B_{\phi 0}\, a/\rho$ for $\rho > a$ then the ropes are unstable to the spiral kink for wavenumber k (in the limit ka << 1) if $B_{\phi 0} > ka\, B_{z0}$ (Hasegawa, 1975). Taking characteristic values of $B_{\phi 0}$, B_{z0} and rope scale radius a (5-10 km), the wavelength of marginal stability is about 90 km, longer than rope scale size a, but shorter than characteristic ionospheric horizontal length scales (thousands of kilometers).

One piece of evidence supporting the helical kink instability is the relative occurrence or fractional volume occupied by flux ropes as a function of altitude. As shown in Figure 2 of Elphic and Russell (1983b), the fractional volume occupied by ropes increases with decreasing altitude, particularly in the region between 0^o and 45^o solar zenith angle. This is to be expected if ropes convect from the ionopause (the upper boundary of the ionosphere) down to lower altitudes due to magnetic tension. As they move into denser ionosphere at lower altitudes, the ropes must push through more mass and, consequently, move more slowly. As they slow, the vertical separation between ropes decreases; more ropes are observed per unit volume. The convection speed V_c varies inversely as the square root of the height-dependent ionospheric mass density, and the flux rope volume density N can be determined from observations of occurrence and scale size. The product of N and V_c should be a constant over all altitudes. Using the actual values, however, the supposedly constant product above in fact varies with altitude, growing systematically from a normalized value of 1 at 300 km and above to 2.8 at 160 km. This suggests that there are more ropes at low altitudes than would be predicted by such a mechanism. In fact, however, the rope volume density N is valid only for downwardly convecting horizontal, straight flux tubes. If the helical kink

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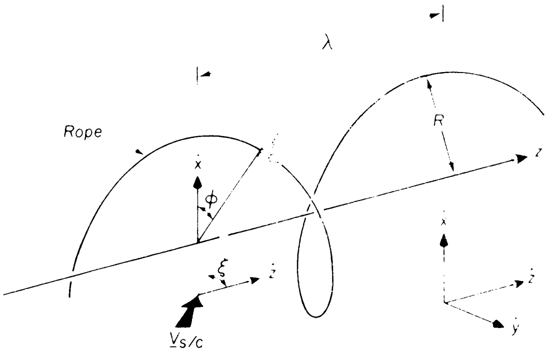

Figure 2. Arbitrary traversal of a flux rope that was helical kink unstable.

instability is producing "corkscrew shaped" flux ropes, the actual volume occupied by the rope increases over that of a simple straight flux rope, since the volume increases as the length of the tube increases due to the helical kink. To match the values above, a helix of pitch ~70^{o} must form by the time ropes convect down to 160 km.

We can independently check the foregoing explanation for the increase in fractional volume occupied by flux ropes by investigating the observed distribution of rope orientations at low altitudes. The results of Figure 6 of Elphic and Russell (1983b) suggest that, for the subsolar regions, the low altitude cases tend to favor vertical orientations, while the cases above 200 km tend to be found in more nearly horizontal orientations. This is qualitatively to be expected of a rope that has gone helical kink unstable.

We can compute the expected distribution of occurrence frequency with inclination i by evaluating the overall probability of observing a flux rope with inclination i, given that it is part of a large scale helical structure whose axis is horizontal. Because the spacecraft trajectory is mainly parallel to the planet's surface at these altitudes, the problem simplifies to the situation shown in Figure 2. Here, the spacecraft trajectory forms the approach angle ξ with the kink spiral axis, and the spacecraft passes through the rope at a helical aximuth ϕ. The probability of observing any particular segment of the helix depends on the effective cross-section of that segment, which in turn depends on whether the flux tube element $\underline{\ell}$ is perpendicular or parallel to the spacecraft trajectory. The probability of observing the rope is maximum when $\underline{\ell}$ is at right angles to the line of sight, but vanishingly small when $\underline{\ell}$ is along the line of sight. The probability of observing a rope at inclination i can be calculated based on helical azimuth ϕ, spiral pitch Θ and approach angle ξ. This quantity must be averaged over all approach angles, in effect summing over all the spacecraft trajectories, to yield an expectation distribution of occurrence of ropes with inclination i.

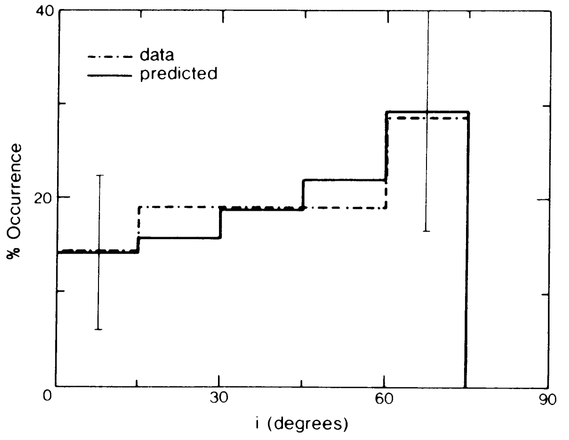

Figure 3. Distribution of the expected and observed occurrence frequency of ropes of inclination i relative to local horizontal. Helical kink pitch is 70^{o}.

Figure 3 shows the resulting distribution of probable occurrence frequency over inclination i given the helical kink pitch angle (solid line) together with the actual observed distribution for the low solar zenith angle cases below 200 km altitude (dashed line). The inclination used here is actually the value defined by $\sin i = |\sin \Theta \sin \phi|$ which folds both downward and upward pointing ropes into the same bin. The pitch ϕ chosen for this distribution is the value producing the best fit, in this case 70^{o}, as compared to a value of 70^{o} inferred from the occurrence vs. altitude results discussed earlier. A pitch of either 60^{o} or 80^{o} gives a poorer fit, suggesting that an average pitch of roughly 70^{o} indeed develops by the time ropes have gotten to altitudes below 200 km.

We may conclude that the magnetic structure of flux ropes indicates they are helical kink unstable for $\lambda > 100$ km. The altitude distribution of the fractional volume occupied by ropes can be explained by invoking the helical kink instability as ropes convect to lower altitudes. Furthermore, the low altitude orientations of ropes can also be explained by helical kink instability. It may be that this instability is at work in other astrophysical phenomena. For example, it may cause filaments of sub-photospheric magnetic flux to protrude into the solar atmosphere.

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