A Uniform-Twist Magnetic Flux Rope in the Solar Wind

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Abstract. We describe magnetic field, proton, electron, and α-particle observations made by WIND on 24-25 October, 1995 of a structure consisting of a magnetic flux rope containing a relatively low beta plasma. While the flux rope structure was inferred from the magnetic field data, the particle behavior corroborates the inference. Minimum variance analysis of the magnetic field data indicates an axis highly inclined to the ecliptic plane and pointing away from the Sun-Earth line. The diameter of the flux rope is estimated as 0.07 AU. Despite a pronounced overpressure, the structure is not expanding but is rather being convected passively with the ambient flow. An intense antisunward field-aligned flow of heat flux electrons indicates that the flux rope is connected at one end to the Sun. The field variation is suggestive of a magnetic flux rope of constant field line twist, and a least-squares fit of this model to the data confirms this to a good approximation. The field line twist per unit length is estimated as ~47 rad AU^{-1}, so that assuming an orientation along the Parker spiral, a given field line has wound ~10 times around the axis from the Sun to 1 AU. In a region inside the tube, the protons, electrons, and alpha particles are hot, the α-to-proton temperature and density ratios are higher than the surroundings, and the α-particles are slower than the protons. Electron and proton anisotropies are negative there ($T_\perp < T_\parallel$). The flux rope does not appear to be related to coronal mass ejections.

INTRODUCTION

Magnetic flux ropes appear in many contexts in astrophysics, solar and space physics. In interplanetary physics, magnetic clouds (1) have been modeled as flux ropes, whether static (2) or self-similarly expanding (3, 4). And the evidence for interplanetary magnetic flux rope structures associated with coronal mass ejections is considered quite persuasive (5). A flux rope not related to coronal mass ejections has also been discussed (6).

A particularly simple flux rope is the uniform-twist field (7). Because of its simplicity, this so-called Gold-Hoyle tube is used extensively in modeling ((4, 8) and references therein)). We present here an observation of such a tube. Two independent methods for determining the magnetic field line twist per unit length agree well with each other. We shall also discuss proton, electron and α-particle data, which show that the structure defined by the field is also reflected in the behavior of the particles, and that the tube is connected at one end to the Sun. There are reasons to believe that this structure is not related to coronal mass ejections. For reasons of space, we display graphically only the magnetic field and proton data and restrict ourselves to a brief description of the other particle measurements. A comprehensive treatment will be reported elsewhere.

MAGNETIC FIELD AND PROTON DATA

Figure 1 shows magnetic field and proton data for the interval from 17 UT October 24 to 09 UT, October 25, 1995. From top to bottom the panels show the proton density, bulk speed, and temperature, the magnetic field strength and its components in GSE coordinates, the proton beta, dynamic pressure, sum of thermal proton and magnetic field pressures, and the Alfven Mach number.

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We shall focus on the stretch of data bracketed by the vertical guide lines. Here a large and smooth rotation of the field in all components occurs in a proton plasma of low β (0.2 - 0.4). (We may anticipate: when the electron and α-particle contribution is added, the total $\beta \leq 0.8$). Aside from a local, small perturbation around hour 26, the declining bulk flow speed is unperturbed and thus the structure is being convected passively past the spacecraft. From hour 22.2 to hour 27.7, the density decreases to the lowest values in the interval shown, the proton temperature rises with the β remaining very low ($\sim$ 0.2), the field jumps to higher values, and Alfven Mach number is low ($\sim$5), the latter implying a strong influence of the magnetic field on the plasma. Since no disturbance due to relative expansion is seen in the flow, the excess pressure (last-but-one panel) is presumably being contained by magnetic tension. Several parameters in Figure 1 show impulsive changes on entry into, and exit from, the structure.

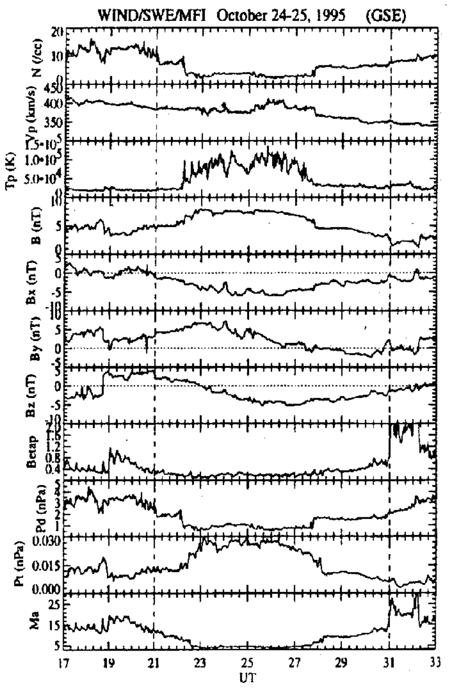

FIGURE 1. Wind magnetic field and proton data for 1700 UT, October 24 to 0900 UT, October 25, 1995. The configuration between the vertical dashed lines is the one discussed in the paper.

Minimum variance analysis

We analyzed the magnetic field data between 21 UT, October 24 to 07 UT, October 25, 1995 by minimum variance (9). The analysis picked out a well defined minimum variance direction (**k**) (ratio of intermediate-minimum eigenvalues, R = 10.5), with unit vectors in the direction of the principal axes (i, j, k) as follows: **i**: (0.0706, 0.8158, 0.5740), **j**: (0.6560, -0.4715, 0.5894), **k**: (0.7515, 0.3349, -0.5684). Minimum variance analysis on the interval where the hot protons are seen, though less reliable (R = 2.6), gives a minimum variance normal subtending an angle of 11° with **k**.

We now assume that the structure represents a magnetic flux rope, an assumption we justify below. For a time-stationary configuration such as this one, we may then identify **k** with a unit vector normal to the tube, **j** with a unit vector along the tube's axis, with **i** completing the right handed triad (10). The flux rope axis is thus inclined at 35° to the ecliptic plane and makes an angle of 24° with the Earth-Sun direction. Taking into account this orientation of the tube and a direction of travel along $-x$ with the average solar wind convection speed past an essentially stationary spacecraft, we conclude from the duration of the observation that the diameter of the tube is $\sim$0.07 AU.

We now work in the flux rope frame. From the approximate symmetry of the magnetic field signature in Figure 1, we conclude that the Wind trajectory passed close to the axis of the tube. Simplifying further, we assume that it intersected the axis, an assumption which changes only the detail of the results reported here. Using this and the tube orientation obtained above, we can express the magnetic field in a coordinate system fixed to the tube. This is done in the first four panels of figure 2 which give the total field for reference, and the radial (B_r), azimuthal (B_ϕ), and axial (B_ζ) field components. Physical quantities are plotted as a function of time, but for a time stationary situation and for a fixed tube orientation, the time can be converted to radial distance from the tube axis, as we do in Figure 3 below. The two-component field of a straight cylindrical tube is evident, with B_ϕ undergoing a bipolar variation, which passes through zero when B_ζ maximizes in absolute value. The amplitude of B_ϕ($\sim$8 nT) is approximately equal to that of B_ζ($\sim$7.5 nT).

The proton flows are shown in the last four panels of Figure 2. The bulk velocity was first subtracted out, and the flow vectors then replotted in a tube frame. The flows are in general weak, about 1% of the total. At the rear boundary of the inner, hot region there is a flow shear where all components reverse sign. Whereas in the forward part of the tube the plasma is practically stationary, there is an evident flow disturbance associated with a flow burst ($\sim$30 km/s) in the rear part of the tube with a small

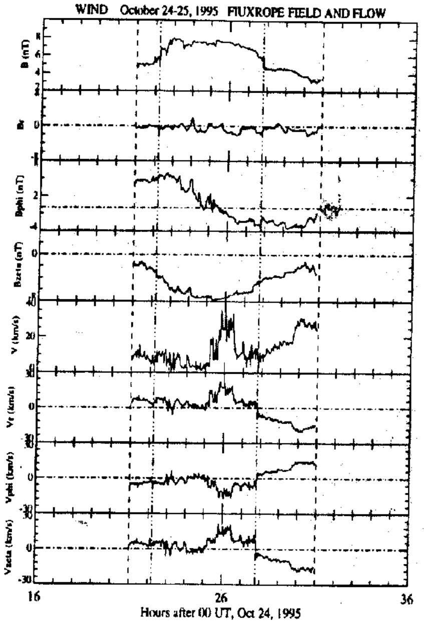

FIGURE 2. The magnetic field and flow vectors in the flux tube frame. The horizontal axis may be transformed to distance from the tube axis because the configuration is stationary.

component along the tube. This might be a temporal feature. If not, then the flows are somewhat problematic to interpret.

Uniform field twist model

The magnetic field observations suggest a simple magnetic field structure. Here we show that a magnetic field of uniform twist ('Gold-Hoyle' tube) reproduces the data well. In this model, the azimuthal and axial field components are, respectively:

$$B_\phi = \frac{B_0 \tau r}{1+\tau^2 r^2}$$

$$B_\zeta = \frac{B_0}{1+\tau^2 r^2},$$

where B_0 is the axial field strength, r is the distance from the tube axis, and τ is the angle a field line turns about the axis in going from one end of the tube to the other, and is the same for all field lines.

A least-squares fit of the model (solid line) to the measured field components (symbols), given in Figure 3, shows that the comparison is quite good. The two free parameters (recall that we assume zero impact parameter) obtained from the fit are B_0 = 7.55 nT and τ = 46.2 rad AU^{-1}. Thus a given field line has turned about 8 times about the axis in 1 AU so that it completes one turn every ~2 x 10^7 km.

An independent check on the result for τ was made by plotting the field line twist per unit length (= $B_\phi / R B_\zeta$) against the distance of Wind from the tube axis. From this we obtain $\tau = 48.3 \pm 62.2$, in substantial agreement with the first estimate. The large standard deviation occurs mainly for small distances r from the tube axis. Since $B_\phi \sim r^{-1}$, a small error in the estimate of r introduces a large uncertainty here. Thus the deviations near $r = 0$ may be improved once we incorporate a non-zero, but small, impact parameter as a third free parameter. In summary, we conclude that the magnetic field data may be represented by a uniformly twisted magnetic flux rope to a good approximation.

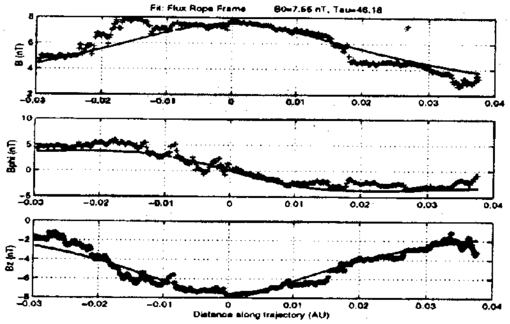

FIGURE 3. A least-squres fit of the field data to a constant-twist magnetic field.

ELECTRONS AND α-PARTICLE DATA

We next give details on electron and α-particle behavior. The electron data from two Wind experiments reveal the following: (a) the boundaries of the tube, determined from the magnetic field, are reflected in the electron behavior. Thus there is a discontinuous density and a temperature rise as we cross the front end of the structure at hour 21. (b) Electron temperatures are higher than proton temperatures and a hot electron population is present together with the hot protons with $\beta_e \approx 2.5\beta_p$. (c) The electrons are slightly anisotropic with $T_{e,\parallel} \approx 1.1 - 1.2 T_{e,\perp}$. (e)

The pitch angle distribution of electrons of energies 121 eV (typical of those carrying the solar heat flux) shows that there is a strong electron flow parallel to the field (antisunward), with much weaker return flows antiparallel to the field, from hour 21 to hour 31 (i.e., in the interval between vertical guide lines in Figure 1). This is the only strong unidirectional flow in the whole 2-day period October 24-25, 1995. This unidirectional streaming of heat flux electrons may be taken as an indication that (a) the flux rope is connected at one end to the Sun, and (b) the flux rope is not related to coronal mass ejections, since these are generally characterized by bidirectional streaming ((5), and references therein).

Turning now to the α-particles, we can summarize observations as follows. (a) Discontinuous behavior in the α-to-proton density ratio, the α-to-proton temperature ratio, and the α-to-proton speeds occur at both boundaries delineating the region of hot protons in Figure 1. (b) The α-to-proton density ratio is low for the time interval from hour 17 to hour 33, but rises to typical solar wind values of 4% in the region where the hot protons are. (c) In this same 'hot proton' region, the α-to-proton temperature ratio, after rising from $\sim$2 to $\sim$8 at the front boundary, decreases slowly to 4. Thereafter it continues to decrease to a value of 2. (d) The α-to-proton velocity ratio is $\sim$1, except in the hot proton region where there is evidence of a consistent relative drift, with the α particles being slightly slower than the protons by $\sim 0.03\ V_p$ ($\sim$12 km s^{-1}).

DISCUSSION AND CONCLUSIONS

We have described magnetic field, ion, and electron observations from instruments on Wind of an interplanetary filament on October 24-25, 1995. We argued that this structure may be represented by a magnetic flux rope of constant magnetic field line twist. The flux rope diameter is $\sim$0.07 AU, and its axis is inclined at 35° to the ecliptic and subtends an angle of 24° to the Earth-Sun direction. Despite the pronounced overpressure, the structure was convecting with the ambient flow without relative expansion.

An inner region was present, marked by abrupt changes in most of the field and particle properties examined. Inside this region, all plasma components are hot, the electron and proton densities are lower than the surroundings, the α-to-proton density and temperature ratios are higher, and the α-particles are somewhat slower than the protons. However, the strong unidirectional flow of heat flux electrons (121 eV energy) extends outside this region and is coextensive with the extent of the flux rope as identified by the large rotation of the magnetic field and shown between vertical guide lines in Figure 1.

Several features argue against this flux rope being related to a coronal mass ejection: the low field strengths, the strong unidirectional flow of superthermal electrons and the short duration being three of these.

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