Final Progress Report on "Some Studies of Flux Ropes in the Earth's Magnetotail"– ISTP Guest Investigator Program

NASA GRANT: NAG 5-4661

June 1, 1997–May, 31 2000.

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Introduction

The objective of the proposal was to understand the formation and evolution of flux ropes in the Earth's magnetotail. For this purpose we proposed to carry out the modeling of the flux ropes observed by the Geotail spacecraft in the middle magnetotail. The modeling of the flux ropes has yielded vital parameters like the scale sizes and the total flux contents of the flux ropes. The modeled parameters were then compared with the solar wind parameters and the magnetotail parameters (local lobe field strength, distance from the Earth etc.) to understand their formation and evolution. A very large data set of field and plasma measurements from the Geotail spacecraft and upstream parameters from the IMP-8 spacecraft was established. In it we identified more than 150 flux ropes and proceeded to model them using the Kivelson and Khurana [1995] model.

Magnetic, particle and solar wind parameter data

We acquired magnetic field (MAG) data set with a time resolution of 3 s for the years 1993-1996 from Dr. S. Kokubun. This data set was supplemented by plasma moments (time resolution 12 sec) from the low energy particle (LEP) instrument from Dr. T. Mukai. The two data sets were combined and converted into flat files for use in the analysis tools developed by our group. We also acquired the spacecraft trajectory, and converted it into flat files. We visually identified more than 150 flux rope events in the acquired data set. The selection criterion is based mainly on the magnetic field. We looked for bipolar signature in the B_z component and a unipolar field enhancement in the B_y component. We also acquired solar wind and IMF parameters from the NSSDC web site for two hours around the flux rope events whenever possible. Out of the 150 flux ropes, roughly one third were found to be single flux rope type events that can be studied using the existing flux rope models. Overall only 31 of the modeled flux ropes also had corresponding solar wind parameters available.

Modeling procedure

Previous models have assumed that the structure is electromagnetically force free, i.e., **j** and **B** are parallel (see e.g. *Elphic et al.*, [1986]). Similarly, *Slavin et al.* [1995] developed a flux rope model with an (electromagnetically) force free central portion surrounded by an elliptical zone which was not in equilibrium. *Kivelson and Khurana* [1995] developed an analytical static equilibrium model (with $\mathbf{j} \times \mathbf{B} = \nabla \mathbf{p}$) which had an array of flux ropes embedded in a Harris neutral sheet. In this model, for any unit cell of the array, the three components of the field in a magnetotail flux rope are given by:

$$B_x = B_L \sqrt{1+\varepsilon^2}\,\sinh(z/L)\chi^{-1} \tag{1}$$

$$B_y = \pm B_L \chi^{-1} \sqrt{(1 - 2\mu_o p_o / B_L^2) + \left(2\mu_o p_o \gamma\varepsilon / B_L^2 \chi^{\kappa-2}\right) + \left(B_{yo}\chi / B_L\right)^2} \tag{2}$$

where

$$\mathbf{B}_z = B_L\, \varepsilon \sin(x/L)\chi^{-1} \tag{3}$$

$$\chi = \left(1+\varepsilon^2\right)^{1/2} \cosh(z/L) + \varepsilon\cos(x/L) \tag{4}$$

and

$$p = \left(p_o / \chi^2\right)\left(1 - \gamma\varepsilon / \chi^{\kappa-2}\right) \tag{5}$$

γ and κ are fit parameters and β is the ratio of thermal pressure to magnetic pressure. For $\beta \neq 0$ and $\gamma\varepsilon \geq 0$, the requirement that both p and B_y^2 remain non-negative for large $|z|$ imposes the constraints: $\kappa \geq 2$ and $p_o \leq B_L^2/2\mu_o$. *Kivelson and Khurana* [1995] set $p_o = B_L^2/2\mu_o$, In this situation, the limit of $\varepsilon \to 0$ reduces to the Harris neutral sheet. It is also clear from (2), that B_y can be of the order of or greater than the lobe field even with $B_{yo} = 0$.

In fitting data from the Geotail to this model we use measured values of B_x to determine the z coordinate as a function of x and B_x from equation (1). We also assumed that the motion in the direction along the tail was uniform at a known velocity during the interval of observation. From the model fit to the observed flux ropes, the total flux and the total current carried by the structures can be inferred.

Modeling results

We have developed a semi-automated least-squares scheme to obtain the best-fit parameters. After the flux rope interval has been identified visually, the program uses a non-linear least-squares inversion routine using a gradient search method to find the best fit parameters. The modeled parameters were then used to find out the total flux content, maximum current density and the total current in the flux ropes.

Below is a list of new findings from this study.

1. A very interesting result is that the parameter ε can often attain values approaching unity. In our previous work when we studied the data from the Galileo spacecraft, this parameter was seen to have values close to 0.3. It also appears that ε increases as a function of down-tail distance.
2. The database of the fit parameters convincingly shows that the flux ropes grow in size as they travel down the magnetotail in agreement with *Moldwin and Hughes* [1992, 1993] results. We observed flux ropes with scale sizes of between 2 and 54 R_E.
3. Though the time resolution of the particle data set is not very high, it appears that fully evolved flux ropes have the plasma thermal pressure at their core as the

plasma sheet in which they are embedded. We do not have any explanation for this intriguing result.

4. The stress balance models of the flux ropes suggest that the as the flux ropes evolve, the current density in the flux ropes should fall inversely in proportion to their scale size. Our modeling results show that $j\,(\mathrm{mA/m^2}) = 17.93\,L^{-0.94}$ which is indeed close to the prediction. This result thus confirms that as the flux ropes evolve they remain in stress balance with their environment.
5. The stress balance model also suggests that the total current in the flux rope should increase in proportion to the scale size of the flux rope. The modeling data base shows that $I(\mathrm{Amp}) = 1.28 \times 10^5 L$, once again confirming that flux ropes remain essentially in stress balance as they evolve.
6. The sense of the core field (B_y) is in the same direction as that of the IMF field. The core current however is always in the dawn to dusk direction. This has an important consequence for the interhemispheric conjugacy of the flux ropes in the ionosphere. The northern (southern) hemisphere intercept is displaced towards (away from) the direction in which the y-component of the IMF points. For both positive and negative IMF B_y, the current should be outward at the early morning end and inward at the late evening end. The unbalanced ionospheric current is expected to close through an imbalance in the substorm current wedge in each hemisphere.

The above results were presented in two national and international meetings.

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Publications/presentations supported by the grant:

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