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Small-scale magnetic flux ropes in the solar wind

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Abstract. Small-scale magnetic flux ropes have been discovered in the solar wind at 1 AU in observations from the IMP 8 and WIND spacecraft. These small magnetic structures (diameter of 270 R_E, on average) have some similar properties to magnetic clouds (diameters of 0.2 –0.3 AU or about 6000 – 8000 R_E), which are well known large-scale magnetic flux ropes, but have durations of 10s of minutes as opposed to many hours or days for most magnetic clouds. The presence of these small helical field structures suggests that solar wind flux ropes may have a wide-range of scale sizes, or possibly have a bimodal size distribution, and are perhaps more common than previously estimated. Similarities and differences with magnetic clouds will be discussed. We suggest that these small scale magnetic flux ropes are signatures of magnetic reconnection in the solar wind as opposed to in the solar corona.

Introduction

Magnetic reconnection in the solar corona [e.g., *Kopp and Pneuman,* 1976; *Hiei et al.,* 1993] has been suggested to be responsible for producing magnetic flux ropes/magnetic clouds that are observed in interplanetary space [*Burlaga,* 1988; *Gosling,* 1990, 1993]. In this model, reconnection occurs on the sunward-side of expanding coronal loops to form the flux rope structure. Magnetic clouds, as defined by *Klein and Burlaga* [1982] and *Burlaga* [1988], are regions with a radial dimension of >0.25 AU (>5800 R_E) at 1 AU in which the magnetic field strength is high and the magnetic field direction changes appreciably by means of a helical rotation of two components of B. Magnetic clouds are inferred to be usually expanding at 1 AU due to a higher total pressure (mainly magnetic field pressure) observed inside the structure compared to the surrounding medium, by their decreasing velocity profiles within the cloud, and by their asymmetric magnetic field profiles [e.g., *Farrugia et al.,* 1993]. Observations from two spacecraft of a magnetic cloud in February 1980 showed that its magnetic field lines can extend continuously from the Sun through the magnetic cloud to the lobe of the geomagnetic tail [*Farrugia et al.,* 1993], confirming the large size of these structures.

Magnetic clouds are a subset of interplanetary coronal mass ejections (ICMEs) [e.g., *Hundhausen,* 1988]. ICMEs and magnetic clouds are often identified by unique plasma and magnetic field properties as compared to the normal solar wind. These include bidirectional ion and electron signatures [e.g., *Marsden,* 1987; *Gosling et al.,* 1987], proton and electron temperature depressions [e.g., *Gosling.* 1973; *Montgomery,* 1974] and low proton plasma beta [*Gosling et al.,* 1987]. Not all ICMEs and magnetic clouds display all of these signatures and not all magnetic flux rope structures observed in the solar wind have been classified as ICMEs.

A small-scale magnetic flux rope was observed by Ulysses on its journey to Jupiter at 5 AU [*Moldwin et al.,* 1995]. It had a diameter estimated to be 0.05 AU (1100 R_E). This structure was argued to be due to magnetic reconnection in the heliospheric current sheet (HCS) opposed to within the solar corona for a number of reasons. These included its small radial size, its correlation with an HCS crossing, and its proximity to a heat flux dropout (HFD). HFDs have been interpreted as evidence of disconnection of interplanetary fields from the solar surface [*McComas et al,* 1989; 1991] (though see *Lin and Kahler* [1992] for an opposing interpretation).

Small-scale tangled and flattened flux ropes have been suggested to exist in the HCS by *Crooker et al.* [1996]. They analyzed several complicated HCS crossings and suggested that intertwined flux tubes can be considered as flux ropes with varying degrees of helicity. These flux ropes within the high beta heliospheric plasma sheet form planar magnetic structures at sector boundaries and are flattened by a combination of compression and kinematic distention. The high beta regime that these magnetic structures were embedded suggested that they were formed near the Sun.

This paper describes the observations from 1 AU of several small scale magnetic flux ropes, discusses the similarities and differences to magnetic clouds and ICMEs, and suggests a heliospheric, opposed to coronal origin for these structures.

Observations

On May 2, 1996, IMP 8 was 32 R_E upstream from the Earth and slightly in the post-noon quadrant while WIND was 83 R_E upstream nearly along the Sun-Earth line. Figure 1 shows the magnetic field data from both IMP 8 and WIND on this date when a small-scale magnetic flux rope was observed. The classic flux rope signature is easily seen with a bipolar turning in Bz (8 nT peak-to-peak amplitude) centered on a relatively strong (8 nT total at WIND) core field. Estimates of the boundaries of the flux rope are shown as vertical lines and these boundaries give a duration of the event between 47 and 57 minutes. The plasma instrument on WIND gives an average solar wind velocity during this interval of 389 km s^{-1} which coupled with a flux rope model gives an estimated diameter of between 191 and 224 R_E.

Figure 1 also shows a simple flux rope model fit [*Lepping et al.,* 1990]. The model describes a force-free magnetic flux rope. The model used is the same as that employed for interplanetary magnetic clouds, since we believe that both these small structures and most magnetic clouds are magnetic flux ropes. The magnetic field configuration in a magnetic cloud at 1 AU is approximately

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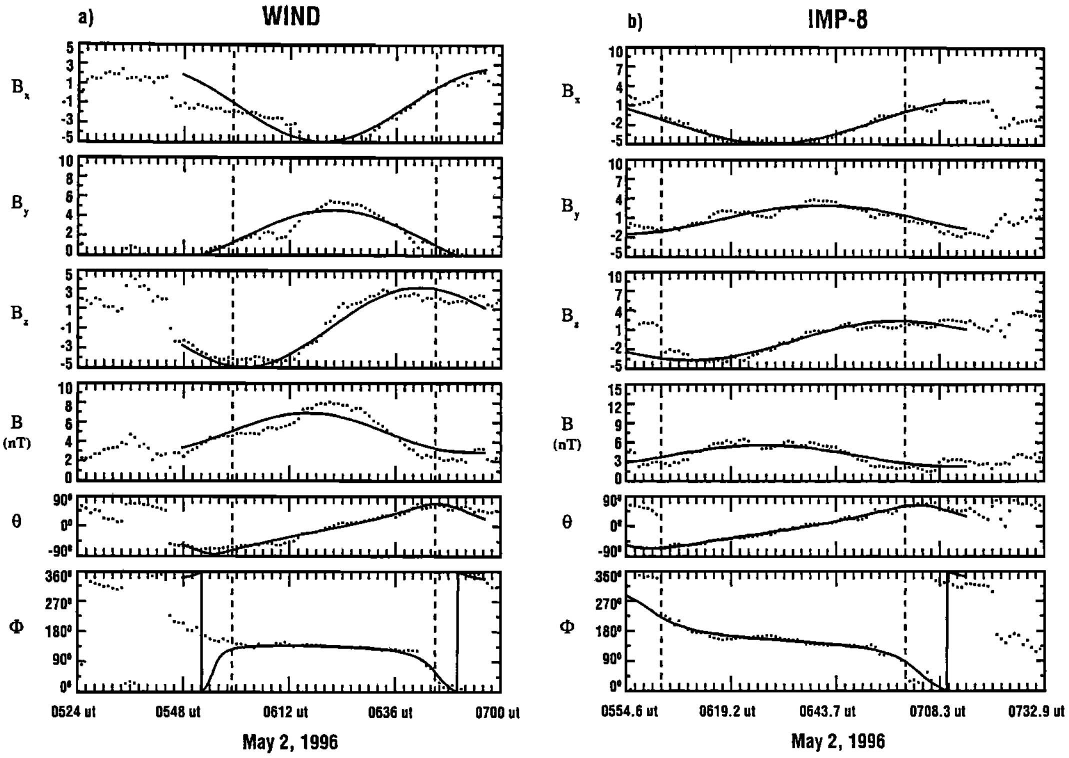

Figure 1. Magnetic field data from WIND (a) and IMP 8 (b) from May 2, 1996. The vertical lines show the estimated beginning and end of the flux rope structure deduced by the behavior in the magnetic field and plasma properties. A flux rope model fit is shown superimposed on the data as a thick solid line. The top 3 panels are the GSE Cartesian magnetic field, the fourth panel is the total field magnitude, and the bottom two panels are the GSE angular Theta and Phi components.

force-free [*Goldstein*, 1983; *Marubashi*, 1986], as these newly discovered small structures appear to be. Evidence in support of the quasi-force-free nature of these small-scale flux ropes include the magnetic field symmetry and uniform velocity profiles signifying the absence of expansion and the low plasma beta (Figure 2). A magnetic flux rope's geometry is that of a nested set of helical field lines confined to a flux tube (see a review by *Farrugia et al.* [1997]). The pitch angle of the helical field lines increases with increasing distance from the axis of the magnetic flux rope, such that the field is aligned with the axis of symmetry at the position of the axis and perpendicular to it on the flux rope's boundary. A useful analytical approximation for this field configuration is the static, constant-alpha (where $J = \alpha B$), force-free, cylindrically symmetric configuration [*Burlaga*, 1988], given by the Lundquist solution of $\nabla^2 B = -\alpha^2 B$, which results from assuming $J = \alpha B$ and the use of Maxwell's equations [*Lundquist*, 1950]. More accurate flux rope models have considered the possibility that magnetic clouds expand as they move away from the Sun [*Burlaga et al.*, 1981] and/or the possibility of a violation of cylindrical symmetry [*Moldwin and Hughes*, 1991]; volume expansion does not seem to apply for these newly discovered small flux ropes, however.

We fit the flux rope model to 1.0 minute averages (in GSE coordinates) of the magnetic field using the same method of Lepping et al. [1990] for the six cases of flux ropes listed here. Initially the least squares fit is made to unit normalized magnetic field data; hence, only the field's direction is considered at first. (A simple linear scaling of the model field magnitude to the observed field intensity is done after the least squares fit, as a final step.) A "reduced"- chi-squared to the fit, $\mathrm{Chi}^2/(3N - n)$, where N is the number of minute-average points and $n = 5$ is the number of parameters in the fit, is used, among other parameters considering symmetry, to measure the quality of the fit; the chi-squared quantity parameter is dimensionless since the magnetic field was unit normalized up to this point. Note that we choose the boundaries of the flux rope such that the magnetic field becomes purely azimuthal there. However, the exact end-points are not always evident, and sometimes many trials were necessary. This method essentially runs synthetic spacecraft through the model flux rope while varying the impact parameter, the core field intensity, and the "twist" of the flux rope (which includes the size of the flux rope and the sign of the helicity). An example of the fitted flux rope of May 2, 1996 as seen by IMP 8 is given in Figure 1b. The fitted curve is deliberately shown outside of the estimated end-points of the flux rope (the vertical dashed lines in Figure 1), as well as for the region of the rope itself, in order to observe the degree of departure of the fit curve from the observations outside. This departure is very clear for the field's direction (the angles) and for the components Bx and Bz. Note that the constant-alpha force-free model provides a good fit to the variation of the direction of the magnetic field and almost as well for the magnitude (this is in contrast to many magnetic clouds that only have a qualitatively good fit for the magnetic field magnitude when using a cylindrically symmetric flux rope model).

The spacecraft nearly intercepted the axis of the magnetic flux rope, Y_0/R_0 being 0.03, where Y_0 is the closest approach distance (C.A.D.) to the magnetic flux rope, and R_0 (= 112 R_E) is the flux

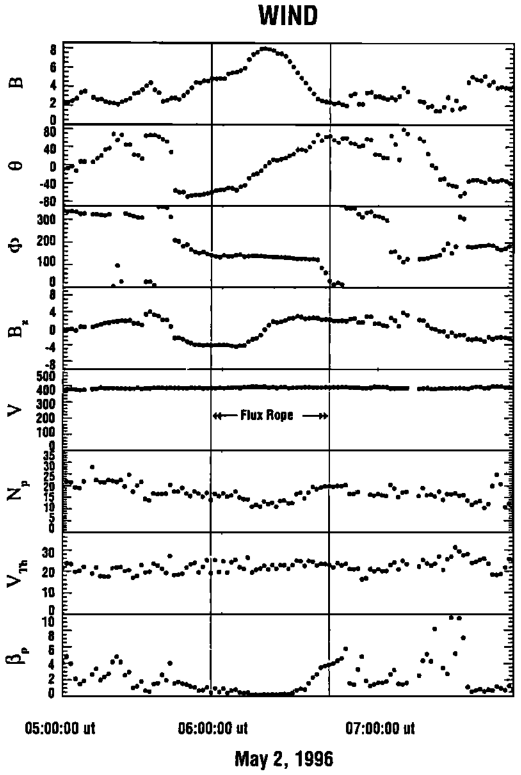

Figure 2. The bulk plasma parameters from WIND for the same event shown in Figure 1a. The magnetic field data are repeated in panel 1-4, while panel 5 shows the bulk plasma velocity, panel 6 the proton number density, panel 7 the proton thermal velocity, and panel 8 the proton plasma beta.

rope's radius. R_0 here is smaller than a typical cloud radius at 1 AU by a factor of about 30. B_0, the estimated field intensity on the rope's axis, is 5.6 nT, which is close to the value of the field at the closest approach (to the axis) point, as seen in panel 4 of Figure 1b.

The plasma parameters from WIND's Solar Wind Experiment are given in Figure 2 for the May 2, 1996 event. The flux rope's boundaries are marked by the vertical lines. The core magnetic field (panel 1) contributes to the large magnetic pressure (not shown) centered on the inflection point of the bipolar turning. The plasma ion pressure (also not shown) is depressed during the interval due to a depression in the ion number density (panel 6). The velocity profile (panel 5) is flat (if not slightly increasing) signifying negligible if any expansion during the transit across the spacecraft. The plasma beta (panel 8) is also very low (0.1 –0.2) at the center of the flux rope.

In all we identified six small-scale flux ropes in the solar wind serendipitously (e.g., we did not do a systematic survey of solar wind data for these events). Four of these events were observed at both IMP 8 and WIND. Table 1 lists some of the physical parameters for each of the events. Note that these six events have estimated diameters ranging from 191 to 530 R_E and have an average duration of about an hour.

Discussion

These small-scale magnetic flux ropes are very similar to magnetic clouds but have several important differences. The main difference is the dramatic disparity in size [*Burlaga et al.*, 1990]. The average estimated diameter of analyzed magnetic clouds observed by WIND at 1 AU is 0.27 +/- 0.11 AU (6350 +/- 2590 R_E) [*Lepping et al.*, 1999]. This is a factor of 20 greater than the average diameters from the sample of this study. We suggest that there are at least two explanations for the difference in size between the two populations. The first possibility is that we are observing the same phenomena with the same origin except we are observing the small size wing of the magnetic cloud size distribution. Many of the magnetic cloud studies utilized hourly averaged data to do their surveys and analysis, and hence they would have missed these small events. However, these surveys did not find any intermediate sized events (durations of several hours), with perhaps one marginal magnetic cloud event of diameter 0.073 AU (1700 R_E) observed by WIND. The second possibility is that these two samples are from two different source regions: magnetic clouds from reconnection in the solar corona, and these small-scale flux ropes from reconnection across the HCS. The radial size of flux ropes formed by reconnection across the Earth's magnetotail current sheet have dimensions similar to the thickness of the current sheet (about a factor of 10 larger) [*Moldwin et al.*, 1991, 1992]. The dimensions of these solar wind small flux ropes have similar scale sizes compared to the HCS (about a factor of 10 larger) [e.g., *Winterhalter et al.*, 1994].

A second difference between these events and magnetic clouds is the different proton temperature behaviors. The proton temperature in magnetic clouds is consistently lower than the ambient solar wind, indicative of the cooler plasma at it's

Table 1.

S/C	Date	Start-Time (UT)	Duration (min)	Vsw (km/s)	Diameter (Re)
WIND	5/2/95	0438	66	475	312
Imp 8	5/2/95	DATA GAP			
WIND	3/13/96	0941	41	574	242
Imp 8	3/13/96	0956	45	574	258
WIND	5/2/96	0554	47	389	191
Imp 8	5/2/96	0557	57	387	224
WIND	9/28/96	1255	65	468	322
Imp 8	9/28/96	1323	44	465	236
WIND	3/18/97	0720	81	371	530
WIND	9/27/97	1514	98	391	484
Imp 8	9/27/97	1523	99	397	516

birthplace on the Sun [*Gosling et al.*, 1973]. By contrast Figure 2 shows very little change of the Vth profile across the small magnetic structure. This was true for all six cases.

A final difference between these small scale flux ropes and magnetic clouds is the lack of expansion of these small magnetic structures; clouds usually are still expanding at 1 AU (though not always). If these structures are formed in the solar corona, they are still different from magnetic clouds since there is no evidence for expansion. Their small size at 1 AU, the flat velocity profile across the structure, and the symmetric magnetic field profiles all suggest that they are not expanding, and are likely from a different flux rope population than large-scale magnetic clouds.

These small-scale flux ropes are also different from the small-scale flux tubes suggested to exist as transient heliospheric plasma sheets by *Crooker et al.* [1996]. That study explained complicated heliospheric current sheet crossings by a planer magnetic structure model. The planer magnetic structure model described the embedded plasma sheets as a layer of small-scale, intertwined flux ropes with varying degrees of helicity, that were flattened into sector-boundary-aligned sheets by kinematic distention and compression. The small-scale flux ropes identified in this study differ from the Crooker et al. flux ropes in a number of ways: (1) the new observations are of isolated magnetic structures whereas the Crooker et al. events consist of multiple flux tubes, (2) the new observations are symmetric implying cylindrical shapes whereas the Crooker et al. events are suggested to be flattened, (3) these new events have very well defined magnetic field rotations whereas the Crooker et al. events only have slight partial rotations, (4) these new events have low plasma betas suggesting that they are force-free structures whereas the Crooker et al. events are embedded in the high beta plasma sheet and suffer from compression and distention, and (5) these new events have well-defined core magnetic fields whereas the Crooker et al. events do not.

Summary and Conclusions

This paper describes a sample of well-defined, small-scale magnetic flux ropes observed at 1 AU by the WIND and IMP 8 satellites. These events have similar properties as magnetic clouds but are significantly smaller and do not have some of the common plasma signatures often associated with magnetic clouds and ICMEs. These structures are also dissimilar to the twisted flux tubes identified by Crooker et al. [1996a]: they are not embedded in the high beta heliospheric plasma sheet, are isolated, are spherically symmetric, and display well ordered complete rotations. We suggest that these observations form a new class of heliospheric magnetic flux ropes whose origins are from magnetic reconnection across the HCS opposed to the solar corona. Evidence for this interpretation include the apparent bi-modal size distribution of interplanetary magnetic flux ropes, the absence of expansion signatures within the flux rope, differences in plasma characteristics such as the proton temperature behavior, and the similarity between their radial scale size and estimates of the HCS thickness. These results suggest that magnetic reconnection in the solar wind maybe a common occurrence.

Future work includes a detailed survey of several years of solar wind magnetic and plasma data for small-scale magnetic flux rope signatures, a study of these small scale magnetic flux ropes impact to the terrestrial magnetosphere, and a detailed study of their plasma and energetic particle characteristics. An interesting question that this future study will address is "what is the size spectrum of magnetic flux ropes in the solar wind?" Is there a continuous size distribution or are there really two distinct size populations?

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