Propagation and evolution of a magnetic cloud from ACE to Ulysses

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[1] The chance of a magnetic cloud (MC) being observed by widely separated spacecraft is rare. However, such an event provides us a good opportunity to study the propagation and evolution of magnetic cloud in the interplanetary space. A magnetic cloud event observed by ACE at Earth on 4–6 March 1998 is tracked from the location of ACE to Ulysses. Using a one-dimensional (1-D) MHD solar wind model, we propagate the ACE data to the location of Ulysses and confirm that the two magnetic clouds observed by both spacecraft have the same solar origin. The Grad-Shafranov (GS) reconstruction technique is then employed to recover the 2-D cross sections of the magnetic clouds at locations of ACE and Ulysses, respectively. The magnetic clouds observed at ACE and Ulysses both show magnetic flux rope configurations of the same chirality and unidirectional axial magnetic field along approximately the same direction. It is found that the magnetic cloud is expanding while propagating outward. Their relevant toroidal (axial) and poloidal magnetic flux contained within each flux rope are different but approximately of the same order of magnitude. However, the relative magnetic helicity contained in each flux rope differs significantly. We discuss the causes of such differences, taking into account the underestimate of the area of the flux rope at Ulysses and the effect of magnetic cloud evolution that may not be fully addressed by 2-D models.


1. Introduction

[2] Coronal mass ejections (CMEs) are spectacular solar events involving the expulsion of $10^{15}–10^{16}$ grams of solar material into the heliosphere [e.g., Hundhausen, 1996, 1997]. Solar wind structures which are the interplanetary counterparts of CMEs at the Sun [Gosling, 1990; Neugebauer and Goldstein, 1997] are now generally referred to as interplanetary coronal mass ejections (ICMEs). Some ICMEs exhibit a smooth rotation of the magnetic field direction through a large angle, enhanced field strength, low plasma temperature, and a low plasma β. Such ICMEs are defined as magnetic clouds (MCs) [Burlaga et al., 1981], which are currently considered to be a subset of ICMEs, comprising about 1/3 of all ICME observations [Gosling, 1990]. Magnetic clouds are the major source of intense, long-duration geomagnetic storms [Gosling, 1990], making them of great importance to space weather studies. Magnetic clouds have been intensively investigated during last 3 decades.

[3] Burlaga [1988] suggested that magnetic clouds at 1 AU can be described reasonably well by a cylindrically symmetric force-free field (a magnetic flux rope structure) with a constant $\alpha$ solution for $\nabla \times B = \alpha(r)B$ [Lundquist, 1950]. Hidalgo et al. [2000] and Mulligan et al. [2001] used axisymmetric, but non-force-free model to fit the magnetic cloud data, respectively. Hu and Sonnerup [2001, 2002] applied a new technique, Grad-Shafranov (GS) reconstruction, to recover the cross section of MC, often of a flux rope configuration, without the assumption of force-free and axial symmetry. GS reconstruction yields an exact fit of the observational data along the spacecraft path, and the boundaries of flux rope are a model output.

[4] Single spacecraft observation alone cannot directly describe the global structures of magnetic clouds and their evolution in the interplanetary space, which should be studied using multiple spacecraft observations. Much attention has been given in recent years to the relationship between ICMEs observed by spacecraft in different locations of the heliosphere [Gosling et al., 1995; McAllister et al., 1996; Skoug et al., 2000; Riley et al., 2003; Reisenfeld et al., 2003; Hanlon et al., 2004; Hu et al., 2005; Paularena et al., 2001; Richardson et al., 2002; Liu et al., 2006]. Because of the rarity of the spacecraft alignments, few events have been observed by radially widely separated spacecraft throughout heliosphere. However, these events are of great importance for studying the evolution of solar wind structures in the heliosphere. The radial expansion of ICME has been studied by some research using a statistical approach [Bothmer and Schwenn, 1998; Liu et al., 2005; Wang et al., 2005] and a theoretical approach assuming self-similar expansion was made by Farrugia et al. [1992].
improvements, which provides an excellent opportunity of conjunct observations with Ulysses. Magnetic field observations are provided by the MAG [Smith et al., 1998] on the ACE and VHM/FGM [Balogh et al., 1992] on the Ulysses.

[7] The rarity of the spacecraft alignments makes it difficult to investigate the magnetic clouds evolution using direct joint observation from ACE and Ulysses. We have already identified the probable ICMEs observed by ACE and Ulysses [Wang et al., 2005], using abnormally low proton temperatures as the primary criteria, which are generally present in ICMEs [Richardson and Cane, 1995]. We first try to relate the ICMEs at Ulysses to those at Earth. As the solar wind propagates outward from the Sun, some ICMEs signatures are evolved through interaction with the ambient solar wind. In addition, the rarity of alignments between ACE and Ulysses makes this task unlikely. Though it is difficult, we did find some ICMEs observed by both ACE and Ulysses. We select the following event that typically exhibits a large rotation of the magnetic filed direction as our first study to be reported.

[8] In March 1998, when the ACE (at ~1 AU) and the Ulysses (at ~5.4 AU) were located near the ecliptic plane with the latitudinal separation of ~2°, and longitudinal separation of ~6°, a magnetic cloud was observed at both spacecraft during this lineup. The event was first observed by ACE on days 63–65 and then passed Ulysses at 5.4 AU on days 82–87. This spacecraft alignment provided a unique opportunity to observe the same magnetic cloud at two very different heliocentric distance and to examine the expansion of magnetic clouds. Skoug et al. [2000] presented an analysis of the plasma, magnetic field, composition, and evolution signatures of this event.

[9] To test whether the magnetic clouds observed by these two spacecraft are the same magnetic cloud event with the same solar origin, we use the solar wind plasma and magnetic field observations by ACE as an input to our 1-D MHD model, follow the propagation and evolution of the solar wind structure to the location of Ulysses, and compare the output with the Ulysses observations. Figure 1 shows the magnetic cloud event observed by ACE in March 1998. From top to bottom, we show the solar wind speed, proton number density, alpha/proton density ratio, proton temperature on a logarithmic scale, magnetic field magnitude and components in RTN coordinate, proton $\beta$, and $T_p/T_{ex}$.

Figure 1. ACE spacecraft observations (1-hour resolution data) near 1 AU. From top to bottom: Solar wind speed, proton number density, alpha/proton density ratio, proton temperature on a logarithmic scale, magnetic field magnitude and components in RTN coordinate, proton $\beta$, and $T_p/T_{ex}$.

[5] In this paper, we try to relate the magnetic clouds observed at Earth to those at Ulysses, based on both in situ observations and our one-dimensional (1-D) MHD model [Wang et al., 2000]. The GS reconstruction technique is thus used to recover their 2-D cross sections. In such a way we study the propagation and evolution of magnetic clouds from ACE to Ulysses. In section 2 the comparison of the observations and 1-D MHD model results is given. In section 3 the cross sections of the magnetic clouds identified as the same event but observed both at Earth and Ulysses are recovered. The results are then discussed and summarized in section 4.

2. Observations and 1-D MHD Model Results

[6] The principal data sets we use are hourly average solar wind plasma, magnetic field, and composition data, which are readily available from both ACE and Ulysses spacecraft. The Solar Wind Electron Proton Alpha Monitor (SWEPAM) experiment on ACE [McComas et al., 1998] provides the bulk solar wind observations. SWEPAM is built from the spare solar wind electron and ion analyzers from the Ulysses mission with selective modifications and
are not perfectly radially aligned and the difference may be also due to the limitation of the spherical symmetry assumption of our 1-D model.

3. Grad-Shafranov Reconstruction Results

Grad-Shafranov (GS) reconstruction technique can be applied to derive the cross section of 2½-D structure of nonaxisymmetric cylindrical flux ropes from in situ single spacecraft measurements. Details of the GS technique and its applications to recover the cross section of magnetic flux rope have been described by Hu and Sonnerup [2001, 2002] and Hu et al. [2003, 2004, 2005]. The magnetic field structures moving past the observing spacecraft are assumed to be in approximate magnetohydrostatic equilibrium, obeying the force balance \( \nabla \cdot \mathbf{B} = \mathbf{j} \times \mathbf{B} \). Structures in a comoving frame of reference, usually the deHoffmann-Teller (HT) frame [e.g., Khrabrov and Sonnerup, 1998], are therefore governed by the so-called Grad-Shafranov (GS) equation:

\[
\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{d}{dA} \left( p + B_z^2/2\mu_0 \right),
\]

where \( A = A(x, y)z \) is the vector potential so that the magnetic field \( \mathbf{B} = (\partial A/\partial y, -\partial A/\partial x, B_z(A)) \), and \( p \) is the plasma pressure. Both \( p \) and the axial field component \( B_z \) are functions of \( A \) alone. The transverse pressure is defined as \( p(A) = p + B_z^2/2\mu_0 \), the only function of a single variable appearing in the right-hand side of equation (1). The \( z \) axis is along the invariant direction of the structure, i.e., \( \partial/\partial z \approx 0 \), and is along the axis of a cylindrical magnetic flux rope to be recovered.

[11] The approach is to first obtain an explicit analytical form of the function, \( p(A) \), from spacecraft measurements. In the HT frame, this is achieved by curve-fitting of known quantity, \( p(x, 0) = p(x, 0) + B_z(x, 0)2\mu_0 \), versus \( A(x, 0) = -\int_0^x B_z(\xi, 0) d\xi \); \( d\xi = -V_{HT} \cdot \Delta t \), along the projected spacecraft path across the structure, \( y = 0 \). By default, the spacecraft is moving across the structure along the positive \( x \) axis. Also, the time dimension is transformed to spatial dimension by using a constant HT frame velocity, \( V_{HT} \). Then the GS equation is solved to obtain \( A(x, y) \) in a rectangular domain [Hu and Sonnerup, 2002; Hu et al., 2004]. In what follows, we apply the GS reconstruction technique to examine the March 1998 magnetic cloud event observed by both ACE and Ulysses at two different distances from the Sun.

[12] Figure 1 shows the magnetic cloud event observed by ACE in March 1998. The interval enclosed by the vertical dashed lines, determined by \( T_p/T_{ex} = 0.5 \) [see Wang et al., 2005], with large magnetic field magnitude and rotation of magnetic field directions, and low \( \beta \) and temperature, clearly marks a magnetic cloud. Therefore it is used as our initial selection of interval for GS reconstruction. However this interval can be adjusted during the analysis [Hu et al., 2004]. It may differ from other choices of interval using different criteria, e.g., low plasma temperature.

![Figure 2. The evolution of solar wind speed with distance.](image)

(a) The observed speeds at 1 AU. (b) The model-predicted speeds 1.4 AU. (c–f) Snapshots of propagated speed in 1 AU increments. (g) Ulysses observations. Dashed vertical lines bracket the boundaries of the magnetic cloud at 1 AU and 5.4 AU.

Figure 3. Comparison of model predictions (solid lines) and plasma and magnetic field parameters (diamonds) observed at Ulysses. From top to bottom: Solar wind speed, proton number density, magnetic field magnitude, alpha/proton density ratio, proton \( \beta \), and \( T_p/T_{ex} \).
Figure 4. Reconstruction results of March 1998 event from (a) ACE and (b) Ulysses data. Each panel shows the cross section of the magnetic cloud. The black contour lines show the transverse magnetic field lines, and the colors show the axial magnetic field, $B_z$, distribution as indicated by the color bar. The yellow (green) arrows along $y = 0$ denote measured transverse magnetic field vectors utilized as initial input into the numerical solver (remaining transverse flow vectors). Their scales are indicated by the horizontal yellow (green) arrow of magnitude 10 nT (100 km/s). The thick white dot marks the location of the maximum $B_z$. The boundary of the embedded flux rope is marked by the white thickened contour line. An alternative arbitrary boundary is marked by the white dashed line.

[13] An excellent HT frame is obtained with correlation coefficient, $cc = 0.9966$, and the Walén slope $w = 0.01$ [Khrabrov and Sonnerup, 1998], indicating small residual flows in the chosen frame of reference. Figure 4a gives the GS reconstruction result of the magnetic cloud. It shows the cross section with transverse magnetic field lines in black contours, and the $B_z$ component superimposed in color. This is a flux rope solution with helical field lines and left-handed chirality. The axial component reaches a maximum ($B_{z_{max}} \approx 12$ nT) near the center of the flux rope. The thick white dot marks the location of the maximum $B_z$. The yellow arrows along $y = 0$ denote measured transverse magnetic field vectors utilized as initial input into the numerical solver. The spacecraft path almost intersects the center of the flux rope, yielding a small impact parameter, $y_0 \approx 0.018$ AU. The boundary of the flux rope, defined as the cylindrical surface of $A = A_b$, is marked by the white thickened contour line. In this case, the boundary of the flux rope is close to the chosen interval of the MC, i.e., the extent of the $x$ axis. The definition of $A_b$ is consistent with the theoretical requirement that the transverse pressure $P_t$ (and/or the axial magnetic field $B_z$) remains the same on one isosurface of the magnetic potential, $A = Const$, within a cylindrical flux rope. The observed $P_t(x, 0)$ versus $A(x, 0)$ and fitted $P_t(A)$ with fitting residue $R_f \approx 0.07$ are shown in Figure 5a. The boundary $A = A_b$ is marked. The fitting residue $R_f$ is a measure of the quality of fit, the smaller value the better fit [Hu et al., 2004]. With the selection of the boundary of the confined flux rope, we obtain the following parameters: the maximum size of the magnetic cloud reaches about 0.25 AU in $x$ and $y$ direction, respectively, which is consistent with the findings at 1 AU by statistical approach, and the toroidal (axial) magnetic flux is $\Phi_t = \int_{A<\text{sub}} B_z ds \approx 9.60 \times 10^{13}$ Wb. The poloidal magnetic flux [e.g., Qiu et al., 2007] can be also calculated as $\Phi_p = |A_m - A_b| L$, where $A_m$ is the $A$ value at the center of the flux rope, and $L$ is an arbitrary length of the flux rope in the $z$ dimension. Despite the uncertainty in estimating $L$, a rough approximation is to assume that the flux rope with two legs anchored at Sun is extending like a circle with a diameter $(D)$ of the distance between the spacecraft and the Sun. In this case, we take $L = \pi D$, where $D \approx 1$ AU. We can estimate the total poloidal magnetic flux, $\Phi_p \approx 4.43 \times 10^{13}$ Wb. We also use the method of Hu and Dasgupta [2005] to calculate the relative (gauge-invariant) magnetic helicity contained within the flux rope. The relative helicity per unit length, $K_r/L$, is $-0.28 \times 10^{-3}$ nT$^2$ AU$^3$. The total magnetic helicity contained in the entire flux rope adopting the simple geometrical consideration given above is $\sim -0.28\pi \times 10^{-3}$ nT$^2$ AU$^3$.

[14] Figure 3 shows the time series of magnetic and plasma data for the same magnetic cloud event observed by Ulysses about 19 days later after ACE observations. An HT frame is obtained with $cc = 0.9991$, but with a large Walén slope, $w = 0.61$. The latter is due to the large magnitude of remaining flow velocities in the HT frame. However, the remaining flow velocities are roughly aligned with the magnetic field vectors and the transverse magnetic field strength is small, so therefore the dynamic effect may still be small [see Hu et al., 2004]. These field-aligned flows probably result from some inhomogeneity along the flux rope axis direction. The recovered cross section is shown in Figure 4b and the fitted $P_t(A)$ is given in Figure 5b. The magnetic cloud has the same left-handed chirality as that obtained at ACE. The maximum axial magnetic field is $B_{z_{max}} \approx 1.38$ nT, which is much lower than that observed by ACE. If we strictly follow the boundary definition of a cylindrical flux rope through the GS technique by Hu et al. [2004], we choose the boundary enclosed by the white thick contour line of $A = A_b$.
in Figure 4b, as also marked in Figure 5b. The toroidal (axial) magnetic flux is $\Phi_t \approx 7.06 \times 10^{11}$ Wb, and the total poloidal magnetic flux is $\Phi_p \approx 1.37 \times 10^{13}$ Wb (now with $D \approx 5.4$ AU). The relative helicity per unit length, $K/L$, is $-0.00135 \times 10^{-3}$ nT$^2$ AU$^3$, and the total magnetic helicity is $\sim -0.0073 \times 10^{-3}$ nT$^2$ AU$^2$. If we relax such a boundary definition and allow a somewhat arbitrary selection as enclosed by the dashed contour line in Figure 4b and marked $A'_b$ in Figure 5b, the aforementioned quantities become, $\Phi_t \approx 1.61 \times 10^{12}$ Wb, $\Phi_p \approx 2.68 \times 10^{13}$ Wb, and the total magnetic helicity is $\sim -0.024 \times 10^{-3}$ nT$^2$ AU$^2$.

[15] The helicity content remains the most different from that obtained from ACE. The main reason is that the size of the flux rope (enclosed by the white thick contour line in Figure 4b) determined from our analysis is much smaller than the magnetic cloud interval. The direct consequence is the underestimate of the area of the flux rope that greatly affects the quantities of magnetic flux and helicity. Further discussions will be given in section 4.

[16] The magnetic clouds observed by ACE and Ulysses have the same chirality and unidirectional $B_z$ component along approximately the same direction (see the caption of Figure 6). The magnetic fluxes are approximately of the same order of magnitude. In particular, the poloidal fluxes obtained from ACE and Ulysses are of greater magnitudes than their corresponding toroidal components, and they agree better. Combined with our 1-D MHD simulation result, we believe that ACE and Ulysses encountered the same magnetic cloud event at two different heliocentric distances. The maximum size of the magnetic cloud increases to about 0.5 AU in $x$ direction; however, the maximum size in $y$ direction does not change much. We find that the magnetic cloud did expand by comparing its cross section at ACE and Ulysses locations. ACE was located at $\sim 7^\circ$S on days 63–65 and Ulysses was located at $\sim 5^\circ$S on days 82–87. ACE was south of Ulysses during this lineup. However, our reconstruction results show that the ACE spacecraft path is slightly north of the flux rope center and Ulysses is south of it, which indicates that the magnetic cloud moved toward the equatorial plane in the latitudinal direction as well while propagating outward.

Figure 5. $P_t(\alpha, 0)$ and $P_t(A)$ for March 1998 event at (a) ACE and (b) Ulysses. Circles are data along the spacecraft inbound path, while stars are along the outbound path. The vertical line denoted by $A_b$ ($A'_b$) marks the point on $A$ axis where $A = A_b$ ($A'_b$). The fitting residue $R_f$ is a measure of the quality of fit, the smaller value the better fit. For details of the boundary determination and the $R_f$ definition, see Hu et al. [2004].

Figure 6. 3D view along positive $R$ direction of the March 1998 event at (a) ACE, and (b) Ulysses spacecraft, respectively (to scale). The spiral lines are magnetic field lines lying on different cylindrical surfaces, winding along the axis of the flux rope to the right. The square to the left is the transverse plane perpendicular to the axis of the flux rope (contour lines on the plane are transverse magnetic field lines). The approximate RTN coordinate directions are depicted in the upper left corner. The local reconstruction coordinates in RTN are (a) $\mathbf{x} = (-0.9364, -0.3460, 0.0587)$, $\mathbf{y} = (0.0066, -0.1689, -0.9856), \mathbf{z} = (0.3509, -0.9229, 0.1584)$, and (b) $\mathbf{x} = (-0.8472, -0.5071, 0.1585), \mathbf{y} = (0.1144, -0.4656, -0.8776), \mathbf{z} = (0.5188, -0.7254, 0.4524)$.
order to show the evolution of the flux rope better, the reconstructed structures in a 3-D view along positive \( \mathbf{R} \) direction of the March 1998 event at ACE and Ulysses spacecraft, respectively, are given in Figure 6 (omitting the nominal difference of the local RTN coordinate at each spacecraft). The axis of the flux rope at Ulysses is tilted slightly away from the direction at ACE. The field line twists are similar at two spacecraft. Since the R component of the invariant z axis is smaller at ACE than at Ulysses, ACE is closer to head-on collision with the magnetic cloud than Ulysses. In addition, a second magnetic cloud was observed immediately following the first at Ulysses on day 87 (a similar structure was observed by ACE but did not satisfy the definition of magnetic cloud). We also use GS reconstruction technique to examine its cross section (not shown). The second magnetic cloud has an opposite chirality to the first. This immediately rules out the possibility that the second one may correspond to the magnetic cloud at ACE.

4. Discussion and Conclusions

[17] A magnetic cloud observed by both ACE and Ulysses spacecraft is of great interest and importance for studying the propagation and evolution of magnetic clouds in the heliosphere. In this paper, we present one example of the likely same magnetic cloud observed by both ACE and Ulysses based on the in situ observations and our 1-D MHD simulation results. GS reconstruction technique is then used to examine the related magnetic cloud events. Various physical quantities are derived by GS method from ACE and Ulysses in situ measurements. Intercomparison of these quantities between the two spacecraft further implies that ACE and Ulysses indeed encountered the same magnetic cloud, despite their radial separation distance of about 5 AU, confirming previous findings [Skoug et al., 2000].

[18] In March 1998 the ACE (at \( \sim 1 \) AU) and the Ulysses (at \( \sim 5.4 \) AU) were located near the ecliptic plane, with the latitudinal and longitudinal separations of a few degrees [Skoug et al., 2000], which can be translated into a few tenths of an AU in distance. Quite remarkably, a magnetic cloud was observed at both spacecraft during this radial lineup, giving us a good opportunity to study the evolution of its cross section. ACE and Ulysses both almost intersect the center of the magnetic cloud, which demonstrates a cross section with an inner core of a nonaxisymmetric cylindrical magnetic flux rope. By examining their cross sections, we conclude that the magnetic cloud expands by a factor of about 2 in radial direction from Earth to Ulysses. The expansion in \( y \) direction is not pronounced and is probably suppressed due to the limitation of our numerical scheme (see, e.g., Hau and Sonnerup [1999], Hu and Sonnerup [2001], and discussion below). In addition, we also find the cross sections recovered from both spacecraft observations have different shapes, probably as a result of the interaction of the magnetic cloud with the ambient solar wind during the course of propagation.

[19] The magnetic fluxes (\( \Phi_0 \) and \( \Phi_D \)) contained in each flux rope at ACE and Ulysses are different but of approximately the same order of magnitude. However, the total relative magnetic helicity differs by at least an order of magnitude. As we pointed out earlier, this is mainly caused by the underestimate of the size of the embedded flux rope at Ulysses, enclosed by the white thick contour line in Figure 4b. In other words, the flux rope embedded within the magnetic cloud at Ulysses may not correspond to the flux rope at ACE in its entirety. Whereas at ACE the embedded flux rope occupies a good portion of the magnetic cloud interval, at Ulysses, it is not the case. Because of the 2-D assumption of our model, the portion that can be recovered and presented here is limited to that best satisfies the configuration of a cylindrical flux rope, albeit the constraint of axisymmetry is removed. In the case at Ulysses, such a portion is significantly smaller than the entire magnetic cloud interval. These may indicate that the magnetic cloud has undergone significant evolution during its propagation from ACE to Ulysses. On the basis of these arguments, we provide a simple estimate of the effect of the underestimated area (thus the toroidal flux) of the flux rope at Ulysses on the value of magnetic helicity as follows.

[20] According to Berger [1999], for example, the magnetic helicity contained in a closed flux rope of constant number of field line twists \( t \) and zero writhe is simply \( 7 \pi t^2 \), where the magnetic flux of the flux rope is denoted \( \Phi \). For our estimation here, we assume the average number of field line twists per unit length, \( \tau \), is approximately the same at ACE and Ulysses (as seen from Figure 6), and substitute \( \Phi_t \) for \( \Phi \). Then we have the ratio of the helicity contained in the flux rope at Ulysses over that at ACE: \( \frac{\pi \Phi_t^2}{\pi \Phi^2} \approx \frac{1}{34} \), well in agreement with the one obtained from our calculations: \( \sim 0.0073/0.28 \approx 1/38 \). For the enlarged boundary (\( A = A_0 \)), such ratios are about 1/7 and 1/12, respectively. This simple estimation shows that our results are consistent within the limit of our model assumptions.

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