Coronal mass ejections (CMEs) are often assumed to be magnetic flux ropes, but direct proof has been lacking. A key feature, resulting from the translational symmetry of a flux rope, is that the total transverse pressure as well as the axial magnetic field has the same functional form over the vector potential along any crossing of the flux rope. We test this feature (and hence the flux-rope structure) by reconstructing the 2007 May 22 magnetic cloud (MC) observed at STEREO B, Wind/ACE, and possibly STEREO A with the Grad-Shafranov (GS) method. The model output from reconstruction at STEREO B agrees fairly well with the magnetic field and thermal pressure observed at ACE/Wind; the separation between STEREO B and ACE/Wind is about 0.06 AU, almost half of the MC radial width. For the first time, we reproduce observations at one spacecraft with data from another well-separated spacecraft, which provides compelling evidence for the flux-rope geometry and is of importance for understanding CME initiation and propagation. We also discuss the global configuration of the MC at different spacecraft on the basis of the reconstruction results.
spacecraft, $T$ is parallel to the solar equatorial plane and points to the planet motion direction, and $N$ completes the right-handed triad. Note that the Sun is at $(−1, 0, 0)$ AU. The flux rope has an axis elevation angle of $\Theta \sim 50°$ and azimuthal angle of $\Phi \sim 270°$ (see § 2). The Earth and STEREO spacecraft, sitting roughly at 1 AU in the solar equatorial plane (see Table 1), would give in situ measurements of the MC along three lines as the MC radially passes these spacecraft. The longitudinal separation between STEREO B and the Earth is about $3^\circ$ (see Table 1), which corresponds to a distance of 0.06 AU, comparable to the flux-rope radius ($\sim 0.07$ AU). STEREO A is about $6^\circ$ or 0.11 AU apart from the Earth. The configuration of these spacecraft provides a great opportunity to test the flux-rope model. In this Letter we reproduce observations at one spacecraft using data from another well-separated spacecraft for the first time, which reinforces the idea of the flux-rope geometry and is potentially important for understanding CME initiation, propagation, and the 3D structure of ICMEs.

2. OBSERVATIONS AND RECONSTRUCTION

Figure 2 shows the plasma and magnetic field measurements of the MC at ACE and Wind. The MC interval is identified by combining the enhanced helium/proton density ratio, depressed proton temperature (compared with the normal temperature expected from the observed speed), and strong magnetic fields with a large rotation. The boundaries also seem consistent with the discontinuities in the proton density, bulk speed, and the total thermal pressure $P$. Temperature measurements are not available for electrons and alpha particles, so the thermal pressure is calculated as $P = 4.5 n_e k_B T_e$ given the plasma charge neutrality and the observed density ratio $n_e/n_p \sim 0.05$, where $k_B$ is the Boltzmann constant. We have assumed $T_e/T_p \sim 3$, $T_e/T_p \sim 4$ as often observed in ICMEs (Liu et al. 2005, 2006a). As expected, Wind and ACE observe almost the same structure due to their small separation. Note that neither the Wind nor ACE data are time shifted. Comparison based on Wind and ACE observations, as discussed above, could not give constraints on the global structure of MCs.

Figure 3 displays STEREO B observations, together with ACE data for comparison. Note that the ACE data are time shifted by 5.3 hr. The MC boundaries at STEREO B are mainly determined from discontinuities in the magnetic field, proton density, and

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Estimated Parameters of the MC at Different Spacecraft</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Start (UT)</th>
<th>End (UT)</th>
<th>$r^*$ (AU)</th>
<th>$\theta^*$ (deg)</th>
<th>$\phi^*$ (deg)</th>
<th>$\Theta^*$ (deg)</th>
<th>$\Phi^*$ (deg)</th>
<th>Chirality</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEREO B</td>
<td>May 22 03:36</td>
<td>May 22 16:34</td>
<td>1.06</td>
<td>$-2.6$</td>
<td>161.8</td>
<td>57.8</td>
<td>262.8</td>
<td>R</td>
</tr>
<tr>
<td>ACE/Wind</td>
<td>May 21 22:19</td>
<td>May 22 12:43</td>
<td>1.01</td>
<td>$-1.9$</td>
<td>164.8</td>
<td>47.8</td>
<td>261.8</td>
<td>R</td>
</tr>
<tr>
<td>STEREO A</td>
<td>May 21 19:12</td>
<td>May 22 00:14</td>
<td>0.96</td>
<td>$-1.1$</td>
<td>170.7</td>
<td>37.6</td>
<td>230.2</td>
<td>R</td>
</tr>
</tbody>
</table>

* Heliographic inertial distance, latitude, and longitude of the spacecraft.
  
* Axis elevation and azimuthal angles in RTN coordinates.
bulk speed, but they are also an output of the flux-rope reconstruction (see below). The STEREO B data within the MC, especially the magnetic field, are apparently different from the ACE data, indicating a sampling at a considerable distance from ACE/Wind. The ambient (particularly the upstream) field is very similar at ACE and STEREO B, so the spacecraft separation is not too large and enables a feasible model-data comparison. The magnetic field is stronger at STEREO B than at ACE, suggestive of a crossing closer to the MC axis.

We reconstruct the MC structure using the Grad-Shafranov (GS) technique (e.g., Hau & Sonnerup 1999; Hu & Sonnerup 2002). The advantage of this method is that it relaxes the force-free assumption and reconstructs the cross section of MCs without prescribing the geometry. Velocity and magnetic field measurements within the MC are transformed into a deHoffmann-Teller frame in which the electric field vanishes (e.g., Khrabrov & Sonnerup 1998). MHD equilibrium is obtained in this frame, i.e., \( j \times B = \nabla P = 0 \), which can be reduced to the GS equation (e.g., Schindler et al. 1973; Sturrock 1994)

\[
\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{d}{dA} \left( P + \frac{B^2}{2\mu_0} \right) \tag{1}
\]

by assuming a translational symmetry (i.e., \( \partial \xi / \partial x = 0 \)). Here \( j \) is the current density and \( \mu_0 \) the permeability of vacuum. The magnetic field can be expressed as

\[
B = \left( \frac{\partial A}{\partial y} - \frac{\partial A}{\partial x}, B_z \right) \tag{2}
\]

through the vector potential \( A \). The thermal pressure \( P \), the axial field \( B_z \), and hence the transverse pressure \( P_t = P + B_z^2/2\mu_0 \) are functions of \( A \) alone (e.g., Schindler et al. 1973; Sturrock 1994). This feature, given by the translational symmetry of a flux rope, is key in testing the flux-rope geometry: if an MC is indeed a flux rope with a translational symmetry, then the behavior of \( P_t \) (and \( B_z \)) versus \( A \) should be the same at different spacecraft.

The purpose of this work is mainly to test this point. The axis orientation of an MC can be determined from the single-valued behavior of \( P_t \) over \( A \) (Hu & Sonnerup 2002). Application of this criterion to the plasma and magnetic field measurements within the MC at STEREO B yields an elevation angle \( \Theta \approx 57.8^\circ \) and azimuthal angle \( \Phi \approx 262.8^\circ \) in RTN coordinates (see Table 1). A flux-rope frame is then set up with the \( x \)-axis along a velocity \( -\mathbf{v}_{HT} \), the \( z \)-axis in the direction of the axial field, and the \( y \)-axis completing the right-handed triad. The HT-frame velocity, \( \mathbf{v}_{HT} = (449, 0.4, -1.8) \, \text{km} \, \text{s}^{-1} \) (RTN), is obtained by minimizing the residual electric field (e.g., Khrabrov & Sonnerup 1998). The right-hand size of equation (1) is derived from the best fit of \( P_t \) versus \( A \) (in the flux-rope frame).

Figure 4 shows \( B \) and \( P_t \) as a function of \( A \) observed at STEREO B. The vector potential along \( x \) is calculated from \( A(x, 0) = -\frac{1}{2} B_y \, dx \). Small scatter around the linear \( B_y \) and second-order polynomial \( P_t \) fits indicates a well-ordered magnetic structure. The best fits should hold over the entire cross section as required by the flux-rope geometry; we will evaluate this feature using a data-model comparison (see below).

Equation (1) can then be solved for \( A \) in a rectangular domain using STEREO B observations as spatial initial values. Away from the observation baseline the vector potential \( A \) is calculated based on its second-order Taylor expansion with respect to \( y \). Note that this integration is intrinsically a Cauchy problem and numerical singularities may arise after a certain number of steps; in general, the integration cannot go further than half of the radial width from the observation line. Differentiation of \( A \) gives \( B_z \) and \( P_t \) through equation (2), while the axial field \( B_z \) and the thermal pressure \( P_t \) can be derived from the best fits (shown in Fig. 4) with the calculated \( A \). The recovered cross section is shown in Figure 5. The contours represent nested helical field lines projected onto the cross section. The field configuration is right-handed, as can be seen from the transverse fields along the trajectory of STEREO B. The maximum \( B_z \) field (presumably at the axis) is very close to the trajectory with an impact parameter \( \approx 0.002 \, \text{AU} \), in good agreement with observations (see Fig. 3).

The path of ACE/Wind, rotated into the flux-rope frame, is about 0.05 AU away from STEREO B in the cross section \((1/3-1/2) \, \text{of the MC radial width})\). For any point along this line, the vector magnetic field as well as the thermal pressure can be obtained from the solutions of equation (1). If the model output at ACE/Wind agrees with the data, then the flux-rope structure as well as the reconstruction scheme can be well verified.
The comparison between data and model output at ACE/Wind is shown in Figure 2 after a transformation from the flux-rope frame into RTN coordinates. The agreement is generally good for both the magnetic field and the thermal pressure. Including the thermal pressure is a unique capability of the GS method, which makes the thermal pressure comparison available. Deviations are also seen but mainly around the dynamical features inside the MC (most visible from the field magnitude and $B_z$). These dynamical features are not in MHD equilibrium assumed in the reconstruction. Numerical errors could also contribute to the deviations. The overall trends, however, are well reproduced. It should be stressed that the reconstruction, in particular the output of and $\vec{v}$, is largely based on the best fits shown in Figure 5. The good data-model agreement justifies the central point that the transverse pressure and the axial field are functions of $A$ alone; combined with the helical fields in Figure 5, this verified feature shows that the MC is a flux rope.

We also reconstruct the MC separately at STEREO A and ACE/Wind. Table 1 lists the times, locations, estimated axis orientations, and field chiralities. These spacecraft were very close to the solar equatorial plane and seemed to observe the MC successively, consistent with their heliocentric distances. The axis orientation is similar at the four spacecraft but with discernible variations. The MC is right-handed at all the spacecraft, as illustrated in Figure 5. It is not clear whether STEREO A observed this event, given a radial width of $\sim 0.06$ AU (5 hr), which is substantially smaller than at STEREO B and ACE/Wind; the timing, axis orientation and field chirality, however, all seem consistent. It is likely that STEREO B observed the flank of the MC (still part of the MC; see Fig. 1). See more detailed discussions of STEREO A observations by Huttunen et al. (2008).

3. SUMMARY

We have tested the flux-rope geometry of CMEs by reconstructing the 2007 May 22 MC observed at STEREO B, ACE/Wind, and likely STEREO A with the GS technique. The pivotal feature of a flux rope we base on is that the total transverse pressure ($P$) and the axial magnetic field ($B_z$) are functions of the vector potential only. The vector magnetic fields and the thermal pressure resulting from reconstruction with STEREO B data generally match ACE/Wind observations. The separation between ACE/Wind and STEREO B is about 0.06 AU, which translates to a distance of $\sim 0.05$ AU in the MC cross section (see Fig. 5) and $\sim 0.04$ AU along the MC (see Fig. 1). If the MC were a spherical plasmoid as suggested by Vandas et al. (1993a, 1993b) the magnetic field would be totally different after a translational distance of 0.06 AU (almost 1/2 of the radial width). Consequently, the multispacecraft MC data reported here cannot be simultaneously fitted using a plasmoid model, although the plasmoid model may fit data at a single spacecraft. Given such a large spacecraft separation (as compared with the MC radial width) and the successful data-model comparison, we conclude that the single-valued behaviors of $P$ and $B_z$ and thus the flux-rope geometry are well validated, at least for the current MC. The reconstruction also shows that the MC is highly flattened, probably due to the solar wind radial expansion as found by Liu et al. (2006b).

The research was supported by the STEREO project under grant NNS5-03131. Y. L. thanks Q. Hu of UC Riverside for helpful discussion. We acknowledge the use of ACE and Wind data. This work was also supported in part by grant NNSFC 40621003.

REFERENCES

------. 1993b, J. Geophys. Res., 98, 21061


[40x308]of point that the transverse pressure and the axial field are functions output of and 
It should be stressed that the reconstruction, in particular the deviations. The overall trends, however, are well reproduced. These dynamical features are not in MHD equilibrium assumed inside the MC (most visible from the field magnitude and $B_z$). Deviations are also seen but mainly around the dynamical features which makes the thermal pressure comparison available. Numerical errors could also contribute to the deviations. The overall trends, however, are well reproduced. It should be stressed that the reconstruction, in particular the output of $B$ and $P$, is largely based on the best fits shown in Figure 4. The good data-model agreement justifies the central point that the transverse pressure and the axial field are functions of $A$ alone; combined with the helical fields in Figure 5, this verified feature shows that the MC is a flux rope.

We also reconstruct the MC separately at STEREO A and ACE/Wind. Table 1 lists the times, locations, estimated axis orientations, and field chiralities. These spacecraft were very close to the solar equatorial plane and seemed to observe the MC successively, consistent with their heliocentric distances. The axis orientation is similar at the four spacecraft but with discernible variations. The MC is right-handed at all the spacecraft, as illustrated in Figure 5. It is not clear whether STEREO A observed this event, given a radial width of $\sim 0.06$ AU (5 hr), which is substantially smaller than at STEREO B and ACE/Wind; the timing, axis orientation and field chirality, however, all seem consistent. It is likely that STEREO B observed the flank of the MC (still part of the MC; see Fig. 1). See more detailed discussions of STEREO A observations by Huttunen et al. (2008). The radial width is nearly the same at STEREO B and ACE/Wind (0.14 and 0.15 AU, respectively). The observed radial widths and the spacecraft configuration reveal a flattened cross section, consistent with the finding of Liu et al. (2006b); if the MC is indeed observed at STEREO A, then half of the transverse size (from STEREO B to STEREO A along $y$ since STEREO B crossed the axis) is at least 0.16 AU and comparable to the radial width, so the aspect ratio may be around 2 : 1 or even larger. Note that ACE/Wind is at a considerable distance from the flux-rope axis (see Fig. 5); reconstruction using ACE/Wind data cannot match observations at STEREO B as well as what we did in Figure 2, which is probably restricted by the integration scheme of the GS method (an intrinsic Cauchy problem).