Geometry of an interplanetary CME on October 29, 2003 deduced from cosmic rays

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Received 21 June 2004; revised 21 June 2004; accepted 24 August 2004; published 6 October 2004.

1. Introduction

A coronal mass ejection (CME) associated with an X17 solar flare reached Earth on October 29, 2003, causing an ∼11% decrease in the intensity of high-energy Galactic cosmic rays recorded by muon detectors. The CME also produced a strong enhancement of the cosmic ray directional anisotropy. Based upon a simple inclined cylinder model, we use the anisotropy data to derive for the first time the three-dimensional geometry of the cosmic ray depleted region formed behind the shock in this event. We also compare the geometry derived from cosmic rays with that derived from in situ interplanetary magnetic field (IMF) observations using a Magnetic Flux Rope model.


2. Observations

Data recorded by three multi-directional muon detectors at Nagoya (Japan), Hobart (Australia), and São Martinho (Brazil) are analyzed here. For detailed properties of the detectors, we refer the reader to Munakata et al. [2000, 2001]. We fit the function $I_{ij}(t)$ given by

$$I_{ij}(t) = I(t)c_{ij} + \xi_{ij}(t)\left(c_1\cos\omega t - s_{ij}\sin\omega t\right) + c^0_{ij}(t)\left(s_{ij}\cos\omega t + c_{ij}\sin\omega t\right)$$

to the pressure-corrected hourly count rates, $I_{ij}(t)$, of cosmic ray secondary muons observed at universal time $t$ in the $i$-th directional channel in the $i$-th muon detector. This yields for each hour the best fit density of primary cosmic rays ($I$, the omni-directional component of intensity) as well as the three components of the streaming vector, or first order anisotropy, in the geographic (GEO) coordinate system $(\xi_x^{\text{GEO}}, \xi_y^{\text{GEO}}, \xi_z^{\text{GEO}})$. In equation (1), $t_i$ is the local time in hours at the $i$-th station, $\omega$ is the angular frequency of the solar wind oscillation, and $c_1$, $c_{ij}$, $s_{ij}$ and $c^0_{ij}$ are so-called “coupling coefficients” which relate the observed muon intensity to the primary cosmic ray intensity in free space [Fujimoto et al., 1984]. We then transform the streaming vector to the geocentric solar ecliptic (GSE) coordinate system and subtract streaming due to solar wind convection and due to Earth’s 30 km/s motion about the Sun, yielding the anisotropy in the solar wind frame $\xi^*$. In these Compton-Getting subtractions, we assume the cosmic ray energy ($E$) spectrum varies as $E^{-2.2}$, and for solar wind speed we employ the hourly mean bulk speed of alpha particles, as the proton bulk speed is unavailable for much of this event (http://umtof.umd.edu/pm/speeds_302-304.gif). In the following analysis, we lag the ACE wind speed and magnetic field data by 20 minutes and passes Earth. Munakata et al. [2004] confirmed this with observations by a network of muon detectors, which respond to higher energy primary cosmic rays (∼60 GeV) than the neutron monitors (∼10 GeV). In the present paper, we analyze muon data using an inclined cylinder to model the geometry of the cosmic ray depleted region. The cylinder is meant to represent a local section of a large-scale loop structure draped from the sun by the CME [Hara et al., 2003]. Preliminary results from earlier events can be found elsewhere [Munakata et al., 2003]; here, we apply an improved analysis method to the extreme event of October 29, 2003.

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0094-8220/04/2004GL020803$05.00
shows that the cosmic ray density $I$ decreased by about 11% following shock arrival at the time of the SSC (vertical line). This is one of the largest decreases ever recorded by muon detectors. There is also a strong enhancement of the anisotropy as shown in Figures 1b and 1c. Figure 1d shows that the GSE x-component ($g_{x}$) of the perpendicular gradient turns systematically from negative to positive, consistent with a cosmic ray depleted region approaching and then receding from Earth. On the other hand, the GSE z-component ($g_{z}$) remains negative, indicating the center of the depleted region passed north of Earth. The GSE y-component ($g_{y}$) turns systematically from positive to negative. These features of a CME passing Earth were first demonstrated from a high latitude neutron monitor network [Bieber and Evenson, 1998]. In the remainder of this paper, we develop a technique for analyzing cosmic ray data using a cylinder model for the CME, and we apply it to the extreme event on October 29, 2003.

3. Analysis and Results

3.1. Cylinder Model for Cosmic Rays

[6] We assume an axisymmetric spatial distribution for the cosmic ray density with a minimum located along the axis of a straight “cylinder,” which is an idealized representation of a local section of a CME loop. In this model, the negative density gradient ($-g_{z}(t)$) observed at Earth is perpendicular to the cylinder axis and points toward the Closest Axial Point (CAP) on the cylinder axis. We assume a simple Gaussian function for the model density distribution,

$$N(r) = N_{0} + n_{0} \exp \left( -\frac{r^{2}}{2\lambda^{2}} \right),$$

where $N_{0}$ is the background density, $n_{0}$ ($< 0$) is the density depression on the cylinder axis, $r$ is distance between the CAP and Earth, and $\lambda$ is a parameter representing the cylinder thickness. The fractional density depression $I(r)$ at $r$ is given by

$$I(r) = \frac{N(r) - N_{0}}{N_{0}} = I_{0} \exp \left( -\frac{r^{2}}{2\lambda^{2}} \right),$$

with $I_{0} = \frac{n_{0}}{N_{0}}$ ($< 0$). The fractional density gradient vector ($g_{\perp}(t)$), which can be obtained from the anisotropy measurement at a position ($r$), is given by

$$g_{\perp}(r) = R_{L} \frac{1}{N} \frac{dN}{dr} = R_{L} \frac{r}{N^{2}} \exp \left( -\frac{r^{2}}{2\lambda^{2}} \right) \approx R_{L} \frac{r}{N} I_{0} \exp \left( -\frac{r^{2}}{2\lambda^{2}} \right),$$

where we used $|I_{0}| = \frac{n_{0}}{N_{0}} \ll 1$ to simplify the expression.

[7] As illustrated in Figure 2, we can determine the position vector of the CAP as viewed from Earth, $P_{E}(t)$, by solving equation (5) for $r$ using the derived $g_{\perp}(t)$ for each hour. The position vector is then given by

$$P_{E}(t) = -r(t) = V_{app}(t - t_{0}) + P_{0},$$

where $V_{app}$ is the apparent velocity of the CAP, $P_{0}$ is its impact parameter, and $t_{0}$ is time of closest approach.
In this paper, we assume the cylinder moves with constant velocity equal to the solar wind velocity \( \mathbf{v}_{\text{sw}} \), averaged over the analyzed time period. The CAP velocity observed in the solar wind frame, \( \mathbf{v}^{\text{app}} \), is then

\[
\mathbf{v}^{\text{app}} = \mathbf{v}_{\text{app}} - \mathbf{v}_{\text{sw}}. \tag{7}
\]

This velocity is aligned with the cylinder axis; hence it defines the orientation of the cylinder.

### 3.2. Best Fitting to the Data

In the actual best fitting analysis, we use equations (4), (5), and (6) rewritten in terms of scale quantities normalized by \( \lambda \), as

\[
I(t) = I_0 \exp \left( -\frac{1}{2} \rho_\xi(t)^2 \right), \tag{8}
\]

\[
g_\perp(t) = -r_L \rho_\xi(t) I_0 \exp \left( -\frac{1}{2} \rho_\xi(t)^2 \right), \tag{9}
\]

\[
\rho_\xi(t) = \mathbf{v}^{\text{app}}(t - t_0) + \rho_0, \tag{10}
\]

where

\[
r_L = \frac{R_L}{\lambda}, \quad \rho_\xi(t) = \frac{P_\xi(t)}{\lambda}, \quad \mathbf{v}^{\text{app}} = \frac{\mathbf{v}_{\text{app}}}{\lambda}, \quad \rho_0 = \frac{P_0}{\lambda}. \tag{11}
\]

We first choose a pair of parameters \( I_0 \) and \( r_L \) and solve equation (9) for \( \rho_\xi(t) \) every hour. We then calculate \( \mathbf{v}^{\text{app}} \), \( \rho_0 \) and \( t_0 \) by fitting a straight line to each GSE component of \( \rho_\xi(t) \) plotted as a function of time \( t \). With these parameters known, we compute the expected density \( I^{\text{exp}}(t) \) and gradient vector \( g^{\text{exp}}_\perp(t) \), and we determine the residual \( S \) defined by

\[
S = \sqrt{\frac{1}{4N} \sum_{i=1}^{N} \left( |I^{\text{obs}}(t_i) - I^{\text{exp}}(t_i)|^2 + |g^{\text{obs}}_\perp(t_i) - g^{\text{exp}}_\perp(t_i)|^2 \right)}, \tag{12}
\]

where \( N \) is the total number of hours analyzed. We repeat these calculations changing \( I_0 \) and \( r_L \), and we determine the best fit pair that minimizes \( S \).

The magnitude of \( \mathbf{v}^{\text{app}} \) can now be calculated from

\[
|\mathbf{v}^{\text{app}}| = |\mathbf{v}_{\text{sw}}| \cos \Theta, \tag{13}
\]

where \( \Theta \) is the angle between \( \mathbf{v}_{\text{sw}} \) and \( \mathbf{v}^{\text{app}} \) for the best fit pair. Using \( R_L \) and \( \rho_0 \) corresponding to the best fit pair, \( \lambda \) and the other parameters are then determined as follows,

\[
\lambda = \frac{|\mathbf{v}^{\text{app}}|}{|\mathbf{v}_{\text{app}}|}, \quad R_L = r_L \lambda, \quad \mathbf{v}^{\text{app}} = \mathbf{v}_{\text{app}} \lambda, \quad \rho_0 = \rho_0 \lambda. \tag{14}
\]

### 3.3. Result

The best fit \( I^{\text{exp}}(t) \) and \( g^{\text{exp}}_\perp(t) \) are shown by the dotted curves in Figures 1a and 1d–1f. The best fit calculations are performed over a time interval \( 3\Delta t = 6 \) hours from 13:00–19:00 UT on 29 October 2003, shown by solid circles. The temporal evolution both of the density and the gradient are well reproduced even with such a simple model. The best fit parameters are given in Table 1. This analysis suggests that the cosmic ray cylinder in this event was inclined at latitude \( \delta = 3^\circ \) from the ecliptic and at GSE longitude \( \phi = 27^\circ \), as illustrated in Figure 3 (left). The scale size \( \lambda \) of the cylinder was \( \sim 0.1 \) AU, which corresponds to a FWHM of 0.28 AU. Closest approach was at 16:27 UT, at which time the CAP passed \( \sim 0.035 \) AU north of Earth.

### 4. Discussion and Conclusion

We have derived for the first time the 3D geometry of a cosmic ray depleted region formed behind a strong interplanetary shock, which arrived at Earth on 29 October 2003, by using the cosmic ray intensity observed with a network of muon detectors. This event caused a \( \sim 11% \) decrease in the omni-directional intensity of cosmic rays. By modeling the cosmic ray depleted region as a cylinder, we demonstrated that the observed systematic variation in the cosmic ray anisotropy is consistent with an inclined cylinder of thickness (FWHM) 0.28 AU approaching and then receding from Earth at the solar wind velocity of

| Table 1. Best Fit Parameters for the Cylinder Analysis of October 29, 2003 |
|----------------------|------------------|-----------------|------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \Delta t \) [hour] | \( \mathbf{V}_{\text{sw}} \) [km/s] | \( B \) [nT] | \( I_0 \) [%] | \( \lambda \) [AU] | \( \mathbf{v}^{\text{app}} \) [km/s] | \( P_0 \) [AU] | \( t_0 \) [hh:mm] | \( R_L \) [AU] | \( S \) [%] | \( \Theta \) [°] | \( \phi \) [°] |
|----------------------|------------------|-----------------|------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 6                    | 1401             | 44              | −11.02                 | 0.119            | 561.7           | −0.001          | 0.005           | 16:27           | 0.056           | 0.342           | 3               | 27              |

*See text for definitions. For vectors \( \mathbf{v}^{\text{app}} \) and \( \mathbf{P}_0 \), the 3 GSE components (x, y, z) are given.
~1400 km/s. The center of the cylinder approached closest to Earth at 16:27 UT on 29 October, at which time it was ~0.035 AU north of Earth.

[14] The best fit Larmor radius $R_L$ in Table 1 is 0.056 AU. Given the observed IMF magnitude of 44 nT averaged over the analysis period ($\langle B \rangle$), this corresponds to an effective rigidity of primary cosmic rays of 112 GV. This value is within the 60–120 GV range of median primary rigidities covered by 39 directional channels in our present network [Munakata et al., 2004]. Noting that no information about the detector energy response was used in the cylinder analysis, the consistency of the inferred effective rigidity with the detector median rigidities supports the validity of the method.

[15] We also performed a best fit analysis of the Magnetic-Flux-Rope (MFR) model [Marubashi, 2000] to IMF data observed by ACE. Shown in Figure 4 are second data of the IMF (a) magnitude, (b) latitude, and (c) longitude. Extending the period of the cylinder analysis interval (delimited by solid vertical lines in Figure 4) is 2.5 times longer than that of the cosmic ray cylinder (dotted vertical lines). Extending the period of the cylinder analysis to later hours is problematic with the present simple model, however, because the fast decrease and slower recovery of the cosmic ray density cannot be modeled by a symmetric Gaussian. Keeping this restriction in mind, we extended the cylinder interval by two hours both earlier and later and obtained inclinations of $13^\circ$ latitude and $56^\circ$ longitude, closer to those of the MFR analysis, though the residual $S$ increased slightly to 0.457 from 0.342 in Table 1. A second reason for a difference is that ACE samples the IMF only along a line determined by the solar wind flow, while the cosmic rays sample the region. We will also work to enlarge the muon observing network in order to obtain a more complete picture of the cosmic ray angular distribution.

[17] Acknowledgments. This work is supported in part by U.S. NSF grants ATM-0207196 and ATM-0000315, and in part by a Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology in Japan and by the joint research program of the Solar-Terrestrial Environment Laboratory, Nagoya University. We thank N. F. Ness for providing ACE magnetic field data via the ACE Science Center.

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