A "loss cone" precursor of an approaching shock observed by a cosmic ray muon hodoscope on October 28, 2003

K. Munakata,1 T. Kuwabara,1 S. Yasue,1 C. Kato,1 S. Akahane,1 M. Koyama,1 Y. Ohashi,2 A. Okada,2 T. Aoki,2 K. Mitsui,3 H. Kojima,4 and J. W. Bieber5

Received 12 September 2004; accepted 22 November 2004; published 11 January 2005.

1Physics Department, Shinshu University, Matsumoto, Japan.
2Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan.
3Faculty of Management Information, Yamanashi Gakuin University, Kofu, Japan.
4Faculty of Domestic Science, Nagoya Women’s University, Nagoya, Japan.
5Bartol Research Institute, University of Delaware, Newark, Delaware, USA.

Copyright 2005 by the American Geophysical Union.
0094-8276/05/2004GL021469S05.00

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L03S04, doi:10.1029/2004GL021469, 2005

1. Introduction

[1] We analyze a loss cone anisotropy observed by a ground-based muon hodoscope at Mt. Norikura in Japan for 7 hours preceding the arrival of an interplanetary shock at Earth on October 28, 2003. Best fitting a model to the observed anisotropy suggests that the loss cone in this event has a rather broad pitch-angle distribution with a half-width about 50° from the IMF. According to numerical simulations of high-energy particle transport across the shock, this implies that the shock is a “quasi-parallel” shock in which the angle between the magnetic field and the shock normal is only 6°. It is also suggested that the lead-time of this precursor is almost independent of the rigidity and about 4 hours at both 30 GV for muon detectors and 10 GV for neutron monitors. Citation: Munakata, K., et al. (2005), A “loss cone” precursor of an approaching shock observed by a cosmic ray muon hodoscope on October 28, 2003, Geophys. Res. Lett., 32, L03S04, doi:10.1029/2004GL021469.

2. Observations

[4] A muon hodoscope has been in operation since May 1998 at the top of Mt. Norikura (geographical coordinates are 36.1°N, 136.6°E and the altitude is 2770 m above sea level) in Japan [Ohashi et al., 1997]. It consists of four horizontal layers of 44 proportional counter tubes (PCTs). Each PCT is a 5 m long cylinder with a 10 cm diameter having a 50-micron thick tungsten anode along the cylinder axis. A 5 cm thick lead layer is installed over the top layer to absorb the low energy background radiation in the air. The PCT axis is aligned in the geographical east-west (X) direction in the top layer and in the geographical north-south (Y) direction in the second and bottom layers. The top and second layers touching each other form an upper pair, while the third and bottom layers form a lower pair. These two pairs are vertically separated by 80 cm. The recording of muons is triggered by the fourfold coincidence of pulses from layers and the incident direction of each muon is identified from X-Y locations of hit PCT in each pair. This is approximately equivalent to recording muons with two 44 × 44 square arrays of 10 cm × 10 cm detectors vertically separated by 80 cm. For initial performance of this hodoscope, readers can refer to prior publications [Fujimoto et al., 2001, 2003].

[5] We analyze the muon intensity recorded in 11 × 11 = 121 directional channels which cover 360° of the azimuth angle and 0° to 55° of the zenith angle. The estimated median energy of primary cosmic rays ranges from 48 GeV for the vertical channel to 80 GeV for the most inclined channel. We first obtain the pressure-corrected hourly count rate in each directional channel, by applying the different correction coefficients for the different zenith angles and thus different atmospheric depths in view. We then normal-
The loss cone precursor observed on October 27–28, 2003. The first and second plots from the top show the 1-hour averages of the IMF magnitude and solar wind speed observed by ACE as functions of time (day of year). The increases of IMF magnitude and solar wind velocity indicate the passage of a shock associated with the Storm Sudden Commencement (SSC) indicated by the vertical line. In the bottom panel, each circle represents the passage of a shock associated with the SSC indicated by the vertical line. The vertical axis in each panel denotes the latitude of the pitch angle during 7 hours prior to the shock arrival at the time of a Storm Sudden Commencement (SSC) indicated by a vertical line.

Following numerical simulations of LC precursors in paper 1, we model the pitch angle distribution of cosmic rays in space by a Gaussian function, as

$$f(\theta, P, \tau) = C_0 \left(\frac{P}{30}\right)^{-1} \exp\left(-\frac{\tau}{T_0(P/30)}\right) \exp\left(-\frac{\theta^2}{2\sigma^2}\right)$$

where $\theta$ is the pitch angle measured from the sunward IMF, $P$ is cosmic ray rigidity in GV, $\tau(<0)$ is the time in hour measured from the SSC onset time, $T_0$ is a free parameter denoting the lead-time (in hours) of LC precursor for 30 GV particles and $C_0(<0)$ is a parameter describing the maximum intensity depression for 30 GV particles at $\tau = 0$ and $\theta = 0^\circ$. We take 30 GV as the typical rigidity of primary cosmic rays modulated in FD and producing the secondary muons. The $1/P$ dependence of LC amplitude on $P$ in equation (3) is assumed to follow the average dependence of the size of FD on particle rigidity. The additional two parameters, $\gamma$ and $\theta_0$, are not used in this model.

Figure 2. The intensity distributions observed in 121 directional channels over 6 hours preceding the SSC. Each panel shows the hourly distribution of muon intensity in a 2D color contour format. Blue color denotes lower intensity. The vertical axis in each panel denotes the latitude of incident direction spanning from the north (upper) and south (lower) directions in the field of view, while the horizontal axis represents the longitude from the east (right) and west (left) directions. The pitch-angle measured from the observed IMF direction is shown by contour lines. The time (hour in universal time) indicated above each hourly map represents the start time of the corresponding hour.
respectively represent the rigidity dependence of the lead-time and the opening angle of the LC.

[9] On the basis of numerical simulations, paper 1 quantitatively related the lead-time \((T_0(P/30)^2)\) and \(\theta_{ observing the half-width'' opening angle \((\theta_{HW})\) of LC, with physical parameters in interplanetary space, such as the local slope of the power spectrum of IMF turbulence \((q)\), the parallel mean free path of the pitch angle scattering of cosmic rays \((\lambda)\) and the angle between the IMF and the shock normal \((\theta_{HW})\). By using \(f\) defined in (3), we calculate the expected intensity \(\Delta I_{cal}^{\text{exp}}(\tau)\) for \(i\)-th directional channel, as

\[
\Delta I_{cal}^{\text{exp}}(\tau) = I_{cal}^{\text{exp}}(\tau) - I_{cal}^{\text{obs}}(\tau),
\]

where

\[
I_{cal}^{\text{exp}}(\tau) = \frac{\int_{P_{\text{min}}}^{\infty} N_i(P) f(\theta_i(P), P, \tau) dP}{\int_{P_{\text{min}}}^{\infty} N_i(P) dP}
\]

and

\[
I_{cal}^{\text{obs}}(\tau) = \frac{1}{121} \sum_{i=1}^{121} I_{cal}^{\text{obs}}(\tau).
\]

In (5), \(N_i(P)\), representing the number of muons produced by primary particles with rigidity \(P\) and recorded in \(i\)-th channel, is calculated by utilizing the response function of muons in the atmosphere to primary particles [Murakami et al., 1979]. \(P_{\text{cut}}\) represents the minimum (cut-off) rigidity of primary cosmic rays to produce muons recorded in \(i\)-th channel. By repeating the calculation of \(\Delta I_{cal}^{\text{exp}}(\tau)\) in (4) for various sets of free parameters, \(C_0, q, T_0\) and \(\theta_0\), we determine the best fit set for \(n\)-hours which minimizes \(S\) defined as

\[
S = \left[ \frac{1}{n} \sum_{j=1}^{n} s^2(\tau_j) \right]^{1/2},
\]

where

\[
s(\tau_j) = \frac{1}{121} \sum_{i=1}^{121} \left( \Delta I_{cal}^{\text{obs}}(\tau_j) - \Delta I_{cal}^{\text{exp}}(\tau_j) \right)^2 \quad \sigma_i\]

and \(\sigma_i\) is the error deduced from the average hourly count rate of muons in the \(i\)-th channel. Note that \(C_0\) can be uniquely determined for each set of \(q, T_0\) and \(\theta_0\). We repeat this best fit calculation by changing the fitting period \(n\) from 7 hours to 12 hours preceding the SSC, until the best fit parameters converge well. We exclude from the best fit computation the hour immediately before the SSC, because the LC center left the field of view by this time.

[10] Table 1 shows the best fit parameters together with the average residual \(S\) in (7), while Figure 3 displays 2D color contours of \(\Delta I_{cal}^{\text{exp}}(\tau)\) reproduced with these parameters. Figure 3 displays a good resemblance to Figure 2 in corresponding hour, suggesting that \(\Delta I_{cal}^{\text{exp}}(\tau)\) is well reproduced with the model distribution in (3). This is also confirmed in Figure 4 showing the scatterplot between \(\Delta I_{cal}^{\text{exp}}(\tau)\) and the best fit \(\Delta I_{cal}^{\text{obs}}(\tau)\). The regression and correlation coefficients in this figure are respectively 1.03 and 0.61.

[11] To examine whether the best fit parameters in Table 1 are consistent with \(\Delta I_{cal}^{\text{exp}}(\tau)\) for each \(\tau\), we also calculate the \(\Delta I_{cal}^{\text{exp}}(\tau)\) on hourly basis, substituting \(f\) in (3) with

\[
f'(\theta, P, \tau) = C_0(\tau) \left( \frac{P}{30} \right)^{-1} \exp \left( -\frac{\tau}{T_0(P/30)^2} \right) \exp \left( -\frac{\theta^2}{2\theta_0^2} \right)
\]

and determine \(C_0(\tau)\) which minimizes \(s(\tau)\) in equation (8). In this calculation, we fix \(T_0, \theta_0\) and \(\gamma\) at the values in Table 1. Figure 5 displays the resulting \(C_0(\tau)\exp(\tau/T_0)\) representing the amplitude of LC at 30 GV in space as a function of \(\tau\). Also plotted in this figure is a curve representing \(C_0\exp(\tau/T_0)\) with \(C_0\) in Table 1. It is again seen that the parameters in Table 1 are consistent with \(C_0(\tau)\) obtained for each hour. Nevertheless, \(C_0(\tau)\exp(\tau/T_0)\) scatters around the curve. In the next section, we will discuss the physical implications of the best fit parameters in Table 1, referring to theoretical results presented by paper 1.

4. Discussion and Conclusion

[12] The “half-width” opening angle \(\theta_{HW}\) is defined in paper 1 as the pitch angle at which the intensity decrease

Figure 3. The intensity distributions reproduced from the best fit parameters in Table 1 and plotted in the same format as Figure 2.
(relative to the omnidirectional intensity) has reached half its maximum value. Taking into account the fact that omnidirectional intensity varies with time in equation (3), we determined that $\theta_{HW}$ is given by 0.893$\theta_0 = 49.1^\circ$ using the parameters given in Table 1. This $\theta_{HW}$ suggests that the LC in this event has a rather broad angular distribution in space. According to a numerical relationship between the loss cone width ($\theta_{HW}$) and $\theta_{BL}$, $\theta_{HW} = 49.1^\circ$ corresponds to $\theta_{BL} \sim 6^\circ$ assuming $q = 0.5$, which implies that the shock in this event is a “quasi parallel” shock (see Figure 7 in paper 1).

On the other hand, using in situ IMF and plasma data we obtain $\theta_{BL} \sim 60^\circ$ from the coplanarity condition. This appears consistent with an “Alaska model” simulation (http://gse.gl.alsaka.edu/). The parent event was either an X1.2 flare (N02W38) at 17:21 UT or another X1.2 flare (S15E44) at 05:57 UT (and/or the associated CMEs) on 26 October 2003 (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES/).

The shock normal angle derived from the loss cone appears to be in conflict with that derived from in situ measurements. We are aware of three possible sources for this seeming conflict. First, the “Alaska model” simulation indicates that a large shock was overtaking a smaller shock westward of Earth. During the loss cone period, Earth may have been connected with the westward shock which is more consistent with a quasi-parallel geometry. Second, there is evidence from multi-spacecraft measurements [Szabo et al., 2001] that interplanetary shocks have a corrugated surface, such that relatively close spacecraft report significantly different shock normal angles. In contrast, the shock normal reported here presumably reflects the large-scale structure of the shock, as it is based upon particles with large Larmor radii (~0.1 AU). Third, it is possible that our current analysis method overestimates the loss cone opening angle, because we neglect (at present) the finite aperture angle of each directional channel, which is about 15 degrees for the vertical channel. In reality, there is a spread of directions from the different angles of incidence in each channel, and this spread may contribute a spurious addition to the computed value of $\theta_0$.

The derived lead-time $T_0$ for 30 GV particles in Table 1 corresponds to the “decay length” $l$ of the LC, as

$$l = T_0 V_s / \cos \theta_{BL} \sim 0.053 \text{AU}$$

The best fit LC amplitude at 30 GV as a function of time ($\tau$) measured from the SSC (solid curve). Also plotted are amplitudes derived from the best fitting on an hourly basis (see text).

References

S. Akahane, C. Kato, M. Koyama, T. Kuwahara, K. Munakata, and S. Yasue, Physics Department, Shinshu University, Matsumoto 390-8621, Japan. (kmuana06@gipac.shinshu-u.ac.jp)
T. Aoki, Y. Ohashi, and A. Okada, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan.
J. W. Bieber, Bartol Research Institute, University of Delaware, Newark, DE 19716, USA. (john@bartol.udel.edu)
H. Kojima, Faculty of Domestic Science, Nagoya Women’s University, Nagoya 467-8610, Japan.
K. Mitui, Faculty of Management Information, Yamanashi Gakuin University, Kofu 400-8575, Japan.