Effects of Coronal Hole Morphology and High Speed Solar Wind Streams on Diurnal Variations in Galactic Cosmic Rays

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Abstract: Data from the Princess Sirindhorn Neutron Monitor at Doi Inthanon, Thailand, with a vertical cutoff rigidity of 16.8 GV, have been utilized to determine the diurnal anisotropy of Galactic cosmic rays (GCRs) near Earth during solar minimum conditions between November 2007 and November 2010. By investigating the synoptic maps of solar coronal holes and solar wind parameters observed by spacecraft, we found that the intensity and anisotropy of cosmic rays are directly associated with the structure and evolution of the equatorial and higher-latitude coronal holes. For example, a strong diurnal anisotropy was observed after the passage of some, but not all, corotating interaction regions. In some cases, a high-speed solar wind stream (HSSWS) from an equatorial coronal hole can merge with that from a trailing mid-latitude extension of a polar coronal hole. Such a slanted HSSWS structure in space, within which the cosmic ray density is depressed, leads to a local latitudinal gradient, which can account for noticeable events of temporary enhancement or suppression (depending on the magnetic field direction) of the diurnal anisotropy at Doi Inthanon. We conclude that the $\mathbf{B} \times \nabla n$ anisotropy associated with coronal hole morphology is a primary source of temporary changes in the GCR diurnal anisotropy under solar minimum conditions.

Keywords: neutron monitor, solar wind streams

1 Introduction

When the Earth rotates, an ecliptic-viewing neutron monitor makes a complete measurement of the cosmic ray pitch-angle distribution once every 24 hours. Cosmic rays of energy up to 500 GeV are affected by the Sun and the interplanetary magnetic field, which introduces an energy-dependent anisotropy [1]. Then the anisotropic flow of cosmic rays is clearly manifest as a diurnal variation of the counting rates of neutrons at ground level. The average diurnal anisotropy vector has been explained as a consequence of the equilibrium established between the radial convection of the cosmic ray particles by solar wind and the inward diffusion of GCR particles along the interplanetary magnetic fields (see [1, 2]). Without drifts and perpendicular diffusion, the corotating streaming is observed as an average corotational anisotropy along the direction of the Earth’s orbit.

During solar minimum, the largest variations of Galactic cosmic rays (GCRs) are associated with expanding high-speed solar wind streams (HSSWSs) with speeds of about 450-800 km s\textsuperscript{−1} from coronal holes (CHs). The CHs are large-scale regions of open magnetic field lines and low-density plasma. The interaction of the HSSWS and upstream slow solar wind of less than about 400 km s\textsuperscript{−1} produces a corotating interaction region (CIR) at the leading edge of the HSSWS. When the CIR passes the Earth, an observer can see a sharp increase in solar wind speed followed by a slow decrease until a new CIR arrives. The CIR appears to be corotating with the Sun and the CH-HSSWS structure is usually stable for more than one solar rotation. GCRs are thus affected by these structures in terms of quasi-periodic 27-day variations that could be clearly noticed in neutron monitor count rates.

Diurnal variations have also been observed to be affected by HSSWSs and CIRs. The average amplitudes of diurnal anisotropies have been reported to be larger than normal during the initial phase of a HSSWS [3].

In the present work, we present observations from the Princess Sirindhorn Neutron Monitor at Doi Inthanon, Thailand during the recent solar minimum, in which the diurnal anisotropy exhibits very different behavior from one HSSWS to another. We present examples in which diurnal variations are enhanced or suppressed according to the $\mathbf{B} \times \nabla n$ for a latitudinal gradient associated with a particular type of coronal hole morphology.
2 Observations and Data Analysis

2.1 Cosmic Rays and Interplanetary Plasma

Cosmic ray data in this study were obtained from the Princess Sirindhorn Neutron Monitor (PSNM). The PSNM is located at the summit of Doi Inthanon, Thailand’s highest mountain, at an altitude of 2,565 m. The vertical cutoff rigidity of 16.8 GV is the highest for any fixed neutron monitor station in the world. For a GCR proton at the vertical cutoff rigidity the Larmor radius would be 0.08 AU in a 5 nT magnetic field. The hourly pressure corrected data from Doi Inthanon for November 2007 to November 2010 have been subjected to harmonic analysis, removing a 24-h running average. From this method, we have determined the resultant amplitude and time of maximum of the GCR diurnal anisotropy.

We utilized the 1-h averaged data of interplanetary plasmas from the MAG and SWEPAM instruments of the Advanced Composition Explorer (ACE) (http://www.srl.caltech.edu/ACE/ASC/level2/index.html), and the OMNIWeb site (http://omniweb.gsfc.nasa.gov/).

2.2 Synoptic Maps of Coronal Holes

The evolution and features of the CHs are characterized by utilizing Fe II 195Å synoptic maps for each Carrington Rotation (CR) from the Extreme Ultraviolet Imager (EUVI) of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) [4] on the Solar Terrestrial RElations Observatory (STEREO) spacecraft. We have examined data from both STEREO spacecraft, STEREO-A (Ahead) and STEREO-B (Behind), but in this report we show only data from STEREO-A.

In order to compare the synoptic maps with the cosmic ray flux and plasma parameters measured at or near Earth we have to correct for the observing angle of (in this case) STEREO-A. First, we assume that the solar wind speed is constant from the source to the Earth (ballistic mapping back in time). In this study, for sake of simplicity we neglect the longitudinal separation between the ACE spacecraft and Earth. The position data in Geocentric Solar Ecliptic (GSE) coordinates of STEREO-A (taken from http://www.srl.caltech.edu/STEREO/attorb.html) are employed to calculate the longitudinal separation between Earth and STEREO-A. The separation monotonically increased during the period of our study, from 20 degrees in November, 2007 to 82 degrees in November, 2010. When comparing data from PSNM and ACE with a synoptic chart from, say, STEREO-A, we must shift the latter to account for the solar wind travel time to Earth and the longitudinal separation, $\Delta \phi$,

$$\Delta t = \frac{1 \text{ AU}}{V_{ACE}} - \frac{\Delta \phi}{\Omega_{\odot}}$$

where $V_{ACE}$ is the solar wind speed as observed by ACE, and for the synodic rotation frequency of the Sun we use $\Omega_{\odot} = 2\pi/26.75$ radians per day [5].

3 Results

3.1 Statistics of the Diurnal Anisotropy at Doi Inthanon

We performed a harmonic analysis using data from the PSNM at Doi Inthanon. For each day (in universal time, UT), the fractional excess count rate $F$ as a function of time was fit to a sinusoid of frequency $\omega = 2\pi/(86400 \text{ s})$:

$$F(t) = D_x \cos \omega t + D_y \sin \omega t$$

where $t$ is the time since the start of the day in UT. The mean values were $\langle D_x \rangle = -0.0002 \pm 0.0009$ and $\langle D_y \rangle = 0.0013 \pm 0.0011$.

Interpreting $(D_x, D_y)$ as a harmonic vector, the mean value has a magnitude $D = 0.0013 \pm 0.0011$ and phase $1.7 \pm 0.7$ radians. In other words, the mean diurnal anisotropy was 0.13%. This phase implies a maximum diurnal enhancement at 6.6 h (UT). Doi Inthanon is located at 18.59°N, 98.49°E, so the true local time (LT) is UT + 6.57 h, and the diurnal enhancement peaks at 13.1 h LT. Based on particle tracing through Earth’s magnetic field [6] and using the response function of [7], coupling coefficients indicate that the asymptotic direction of peak diurnal anisotropy is close to the Equator and offset by 62.5° from the longitude of Doi Inthanon (T. Kuwabara, private communication, 2010). This offset indicates a peak flux from the direction of the magnetic field ($B_{\odot}$) increased. The positive polarity CHs (B and C) were located in the Southern hemisphere and another, isolated CH (A) of negative polarity was located near the solar equator and the heliospheric current sheet (HCS). During the times of recurrent solar wind streams, there were accompanying compressions of density ($n$) and magnetic field ($B$). At the leading edge of the streams, the root-mean-square of the interplanetary magnetic field ($B_z$), average field magnitude ($B$), entropy, and proton density ($n_p$) increased. The direction of the magnetic field ($B_z$ and longitude of magnetic field) and latitude of solar wind flow are reversed. Each HSSWS occurred in two types of magnetic sectors. In the negative magnetic sector $\phi_B$ is close to 315° and in the positive polarity sector $\phi_B$ is close to 135°, consistent
Figure 1: Reversed time plots in day of year (DOY) for CR2071 (between 2008 June 12 and 2008 July 10). Top panel: Synoptic map of the solar corona as observed by the EUVI-A imager in the Fe II 195 Å bandpass. Lower panels: hourly interplanetary plasma parameters from the ACE and OMNIWeb databases in GSE coordinates. When the HSSWSs pass the Earth they reduce the cosmic ray flux. Each dotted-dashed line represents a boundary between magnetic polarities of the streams. After the CIR of DOY 177, there was a strong, long-lasting enhancement in the diurnal anisotropy (DA) of GCRs. We attribute this to an extra $B \times \nabla n$ anisotropy with a latitudinal gradient in association with the coronal hole (CH) morphology.

With their origins in the coronal holes of similar polarity as shown in Figure 1, in CR2071 (2008 June 25), we observed a long-lasting enhancement of diurnal amplitude for 12 days after the passage of a CIR. The average diurnal amplitude is 0.33% and the phase is nearly constant at around 0700 UT. The peak speed value of the HSSWS was 624 km/s on DOY 178 (26 June 2008). The enhanced diurnal anisotropies coincide with the HSSWS of positive polarity-CHs (at the equator and as a mid-latitude extension of the south polar CH, or B and C, respectively). Their corresponding streams are evidently merged to be a compound stream. The HSSWS should therefore be slanted with respect to the solar equator, which should lead to a density gradient perpendicular to its boundary. Consequently, the compound HSSWS from the positive polarity CHs in CR2071 should have a net latitudinal gradient of cosmic rays toward the south. This should cause an additional anisotropy in the ecliptic plane via the $B \times \nabla n$ drift flux.

If $B$ is in the ecliptic plane, a gradient in that plane would lead to a $B \times \nabla n$ anisotropy in the North-South direction, which would make little contribution to the DA. However, a latitudinal gradient, such as that caused by the CH morphology (B and C in Figure 1), can lead to an extra $B \times \nabla n$ anisotropy that enhances or suppresses the usual DA, which is in the $-y$ direction, depending on the sign of $B_z$. After the CIR of DOY 177, $B_z$ was negative, which in combination with the southward GCR gradient, leads to a $B \times \nabla n$ anisotropy along $-y$, thus enhancing the usual corotational anisotropy.

Before the 25 June 2008 CIR event we observed other long trains of enhanced diurnal anisotropies that were smaller in amplitude (not shown here) and remained until CR2072. Over the half Carrington Rotation prior to DOY 177, diurnal variations of GCRs were low during the HSSWS from the negative polarity CH (A) in Figure 1 that has a horizontal letter-V morphology. The same characteristic is found starting from CR2068. From the correction of time differences between Earth and STEREO-A, we noticed that the enhancements have “quasi-periodic recurrences” produced by the quasi-periodic HSSWS traversals.

4 Discussion and Conclusions

The long-lasting enhancement of diurnal anisotropy during part of CR2071 is closely related to the HSSWS from an equatorial CH, which merged with that from a trailing mid-latitude extension of a polar CH produce a slanted HSSWS structure in space, within which the cosmic ray density is depressed. This leads to a local latitudinal gradient. Such a gradient can account for noticeable events of temporary enhancement or suppression (depending on the magnetic field direction) of the diurnal anisotropy.

For the example in Figure 1, the fast wind emitted by the first CH (B) has merged with the trailing streams from another higher-latitude CH (C) which form a CIR with a large latitudinal extent. When this slanted morphology is present, the latitudinal effect should be considered. GCRs scattered by the compressed IMF cannot refill the depleted regions easily as they are forced to propagate around the
slanted structure at which the larger and higher-latitude CH (C) has larger effect to diurnal variations. In addition, the presence of kinematic steepening [9] and CIR formation may prevent GCRs from recovering as could be seen from the train of roughly constant GCR intensity within the structure.

In general, short-term cosmic ray intensity variations are driven by solar wind structures in low- and middle-latitude regions, such as CIRs that change the particle diffusion properties in association with their passages (10 and references therein). Previous work has remarked on the importance of the latitudinal density gradient in the inner heliosphere for long-term averaged equatorial diurnal anisotropies [11]. The three-dimensional structure of GCR (∼10 GV) anisotropies associated with solar rotation was determined for 27-day spectral peaks in long-term data sets. The corotating azimuthal and latitudinal gradients were found to be about twice the steady-state radial gradient (∼3% per AU). This was interpreted [11] by using the cosmic ray B × ∇n drift in which the component of the corotating gradient perpendicular to the ecliptic gives rise to the 27-day periodicity in the diurnal variation. In the weak-scattering limit (when the collision frequency ν is negligible), the fluxes driven by perpendicular diffusion are small compared with those driven by B × ∇n [12]. Therefore, we expect that the enhancement or reduction in magnitude of the diurnal variations is dependent on the latitudinal gradient of the GCRs as affected by the HSSWSs near Earth.

In this work we have observed features of CHs that could explain the latitudinal gradient. The slant of the HSSWS morphology due to the merger of streams from two CHs can produce a large-scale latitudinal GCR density gradient. Apparently, the B × ∇n anisotropy plays an important role for quantitative understanding of short-term variations in the diurnal anisotropy of GCRs.

Acknowledgements

This research was partially supported by the Thailand Research Fund (TRF). We are grateful for support from the Thai Ministry of Science and Technology (MOST).

References