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Neutron monitor asymptotic directions of viewing during the event of 13 December 2006

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Abstract

During the recent ground level enhancement of 13 December 2006, also known as GLE70, solar cosmic ray particles of energy bigger that ~500 MeV/nucleon propagated inside the Earth's magnetosphere and finally accessed low-altitude satellites and ground level neutron monitors. The magnitude and the characteristics of this event registered at different neutron monitor stations of the worldwide network can be interpreted adequately on the basis of an estimation of the solar particle trajectories in the near Earth interplanetary space. In this work, an extended representation of the Earth's magnetic field was realized applying the Tsyganenko 1989 model. Using a numerical back-tracing technique the solar proton trajectories inside the magnetospheric field of the Earth were calculated for a variety of particles, initializing their travel at different locations, covering a wide range of energies. In this way, the asymptotic directions of viewing were calculated for a significant number of neutron monitor stations, providing crucial information on the Earth's "magnetospheric optics" for primary solar cosmic rays, on the top of the atmosphere, during the big solar event of December 2006. The neutron monitor network has been treated, therefore, as a multidimensional tool that gives insights into the arrival directions of solar cosmic ray particles as well as their spatial and energy distributions during extreme solar events.

Keywords: Magnetospheric field; Asymptotic directions of viewing; Cosmic rays; Neutron monitor; Modeling

1. Introduction

Neutron monitors located at different places on the Earth's surface record secondary particles originating from primaries that come in general from different directions in space. Charged galactic and solar cosmic ray particles approaching the Earth encounter its geomagnetic field. If they are sufficiently energetic they can propagate inside the magnetosphere and enter the Earth's atmosphere. Products of the interaction of these particles with the molecules of the atmosphere, access ground level neutron monitors located at different sites around the globe. Due to the geometry of the geomagnetic field the rigidities of primary cosmic ray particles responsible for the counting rates registered at ground level have values bigger than the respective cut-off rigidity of the specific site. Moreover, due to the particle motion inside the geomagnetic field, each ground level detector is capable of recording particles produced by primaries originating from a limited set of directions in space, which is called asymptotic cone of viewing. The problem of defining these asymptotic directions of viewing for a specific neutron monitor has been always of great interest and therefore several efforts for calculating the cut-off rigidities as well as the particle trajectories and the asymptotic cones of viewing have been made over the years (McCracken et al., 1962, 1968; Shea et al., 1965; Smart et al., 2000). However, due to the complexity of the real magnetospheric field of the Earth, the problem of defining the particle trajectories inside the magnetosphere has no solution in closed form yet.

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Due to the fact that each neutron monitor records secondary particles produced by primaries originating from different parts of the sky, it is proved to be a magnetospheric window in the near Earth interplanetary space providing crucial information on the Earth's "magnetospheric optics" for primary cosmic rays (Plainaki et al., 2007). Getting this information at ground level is very important and can be utilized in means of space weather monitoring and forecasting. The neutron monitor network, as a whole, can be consequently treated as a multidimensional tool that gives insights into the arrival directions of solar cosmic ray particles as well as their spatial and energy distributions during several cosmic ray events (Plainaki et al., 2007; Mavromichalaki et al., 2007). A significant number of solar extreme events resulting in count rate increase of the cosmic ray intensity registered at ground level neutron monitors took place during the descending phase of the 23rd solar cycle. Several studies on the ground level enhancements (GLEs) of October–November 2003 (Plainaki et al., 2005; Eroshenko et al., 2004; Bieber et al., 2005) and January 2005 (Plainaki et al., 2007) have been realized. Recently, on 13 December 2006, a new GLE was registered at the worldwide neutron monitor network. This GLE was the third biggest GLE of the current cycle of solar activity, leaving behind only the enhancements of 15 April, 2001 and 20 January, 2005 having a magnitude of ~92% recorded at Oulu Neutron Monitor.

The peculiarities and differences between the intensities of secondary solar particles occurring between different neutron monitor stations during the ground level enhancement of 13 December 2006 can be interpreted on the basis of their asymptotic directions of viewing during that exact period. In this work, an effort for calculating the asymptotic directions of viewing for a significant number of neutron monitors stations widely distributed around the globe covering a wide range of latitudes, longitudes and rigidities has been made using the Tsyganenko 1989 magnetospheric field model for the time period of the big solar cosmic ray event of December 2006 (GLE70).

2. Asymptotic directions of viewing calculation method

Incoming charged particle trajectories to various locations on the surface of the Earth can be traced if the Earth's magnetospheric field is well defined. The equation of motion is expressed as

$$\ddot{\vec{r}} = e/mc \cdot \dot{\vec{r}} \times \vec{B} \tag{1}$$

where $\ddot{\vec{r}}$ is the particle acceleration, $\dot{\vec{r}}$ is the particle velocity, and $\vec{B}$ is the magnetic field vector. The electronic charge is denoted by e, m is the particle's relativistic mass, and c is the speed of light.

In the current analysis, in order to describe the Earth's magnetospheric field, we have used Tsyganenko 1989 model, which is a semi-empirical best-fit representation, based on a large number of satellite observations (IMP, HEOS, ISEE, POLAR, Geotail, etc.), providing quite a realistic description of the field configuration in the magnetosphere (Tsyganenko, 1989). The model includes the contributions from external magnetospheric sources: ring current, magnetotail current system, magnetopause currents and large-scale system of field-aligned currents. It also takes into consideration the seasonal and diurnal changes of the magnetospheric field as well as the geomagnetic activity level Kp. In contrast with the majority of previous geomagnetic field models (e.g. Tsyganenko, 1987), the Tsyganenko 1989 model takes into account the effect of the current sheet warping. This means that it is built in such a way as to account that for non-zero tilt angle ψ between the z-GSM axis and that of the Earth's dipole the average shape and position of the tail neutral sheet undergoes a two-dimensional warping (Russell and Brody, 1967; Fairfield, 1980; Gosling et al., 1986). Near the midnight meridian plane the warping results in a gradual departure of the current sheet from the dipole equatorial plane towards that parallel to the solar wind stream. This is accompanied by a bending of the sheet in the YZ projection in such a way that, for $\psi > 0$, the current surface is raised above the GSM equatorial plane in the central tail region, whereas it is depressed below this plane near the tail flanks (and vice versa for $\psi < 0$). The geometry of the current sheet according to the Tsyganenko 1989 magnetospheric field model, for the time period of GLE70 (tilt angle ~31.88°) is demonstrated in Fig. 1. The current sheet geometry of the geomagnetic filed is very important for the calculation of the particle trajectories, since it reflects the distribution of the magnetic field lines. Therefore, taking it into account results in a more accurate and reliable representation of the field and consequently in a more detailed calculation of the neutron monitor asymptotic directions of viewing. Nevertheless, one should notice that apart from the Tsyganenko 1989 model there is a variety of other magnetic field models, suitable also for geomagnetically disturbed periods (Kudela et al., 2008). However, because of the fact that this event took place during a moderate geomagnetic disturbance, their use would not affect significantly the present results.

In order to calculate the particle trajectory inside the magnetic field a numerical back-tracing trajectory technique has been used. Charged particles are assumed at the site of each ground level detector and their path as they are moving away from the detector is being traced. The trajectory starts from the observational site and is traced back by reversing the particle's velocity vector and the sign of charge. Particles of the same rigidity (momentum per unit charge) but opposite charge will follow the same path through the field as particles arriving from the sun. The computed trajectory is defined as allowed if it crosses the magnetospheric boundaries whereas it is defined as forbidden if it rests on the Earth's surface or it remains trapped within the magnetosphere. Thus rigidity dependent viewing directions can be determined for each observational site and therefore independently for each neutron monitor. One should note that in many cases (as in this analysis) it

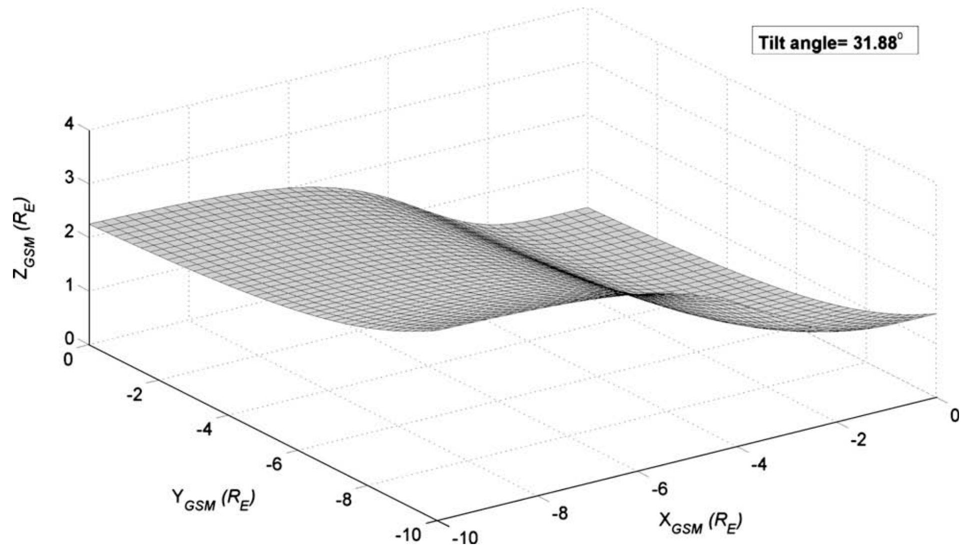

Fig. 1. Geometry of the current sheet on 13 December 2006 during the time period of GLE70. The unit along X, Y, Z axes is the Earth's radius (R_E).

is sufficient to consider only those particles arriving with vertical incidence at the detector. Since the system expressed by Eq. (1) consists of three simultaneous differential equations with six unknowns (three accelerations and three velocities expressed in spherical coordinates) the problem of defining the particle trajectory and motion can be solved numerically on the basis of Runge Kutta Method (Ralston and Wilf, 1960).

3. Results and discussion

For the time period of 13 December 2006 the asymptotic directions of viewing calculated for a big number of neutron monitor stations widely distributed around the globe covering a wide range of vertical cut-off rigidities are shown in Fig. 2. Assigning the term "neutron monitor asymptotic cone" to the set of allowed trajectories traces at the altitude of ~80 km above the Earth surface for this specific station, the magnetospheric windows for all the existing worldwide neutron monitor network were defined (Fig. 2). Commenting Fig. 2, one should point out that each point refers to a particular rigidity. For example, particles that reached the NM of Oulu, in the time period of GLE70, produced from primaries of rigidity of ~1 GV originated from (long = 22.68°, lat = 2.99°), whereas those produced from primaries of rigidity of ~2 GV came from (long = 80.24°, lat = 2.08°), at the altitude of 80 km. For a mid latitude station the situation changes. For example for Moscow NM station the primaries of rigidity of 2.6 GV, producing the respective NM fluxes, originated from (long = −172.05°, lat = 9.37°).

In Fig. 2, it is clearly revealed that the counting rates registered at different observational sites correspond to primary particle fluxes originating from different points of the sky. This fact can give explanation to various questions arising from the observations. Fore example, during the ground level event of December 2006, some low cut-off rigidity neutron monitor stations (e.g. McMurdo) recorded enhancements of significantly smaller magnitude in comparison with those registered at other stations of the same cut-off rigidity (e.g. Apatity, Oulu). Moreover, these differences were even bigger during the initial phase of the event. At this point it should be stated that in the general case of an anisotropic GLE, the source of anisotropy above the Earth's atmosphere is located at some specific position, which may or may not change with time. Therefore, any differences in the counting rates of the ground level neutron monitors of the same cut-off rigidity can be possibly attributed to different asymptotic directions of viewing between these stations in relation to the location of the source of the anisotropic solar particle flux. In other words, stations with asymptotic cones at the most favourable positions are those that record the maximum effect, whereas other record smaller increases or not enhancements at all. Results of the calculation of the position of the anisotropy source during the time period of GLE70 on the basis of the NM-BANGLE model, showed that the solar particle anisotropic source must have been located close enough to the ecliptic plane (Plainaki et al., in press). This seems to be also the reason why this event was recorded bigger at sub-polar stations and not at polar ones, as it happens usually during GLEs.

The position of the anisotropy source during the initial phase of GLE70 event (at 3:05 UT), extracted from the application of the NM-BANGLE model, in relation with the asymptotic directions of viewing of several neutron monitors, is demonstrated in Fig. 3. The solar energetic particles seemed to have arrived forming a narrow beam that could be sensed better by those neutron monitors with asymptotic cones in the most favourable positions in relation to the beam (e.g. Apatity, Oulu, Mawson). Other stations with asymptotic viewing direc-

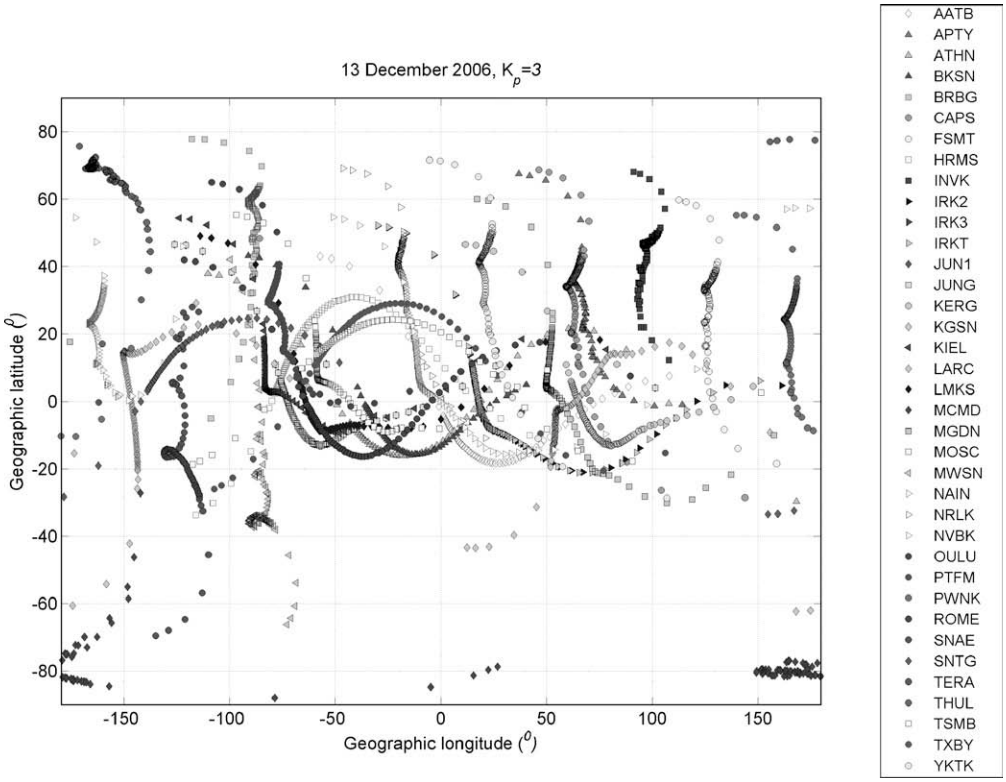

Fig. 2. Asymptotic directions of viewing for the neutron monitors of the worldwide network. The calculation step in rigidity scale was taken as 0.1 GV.

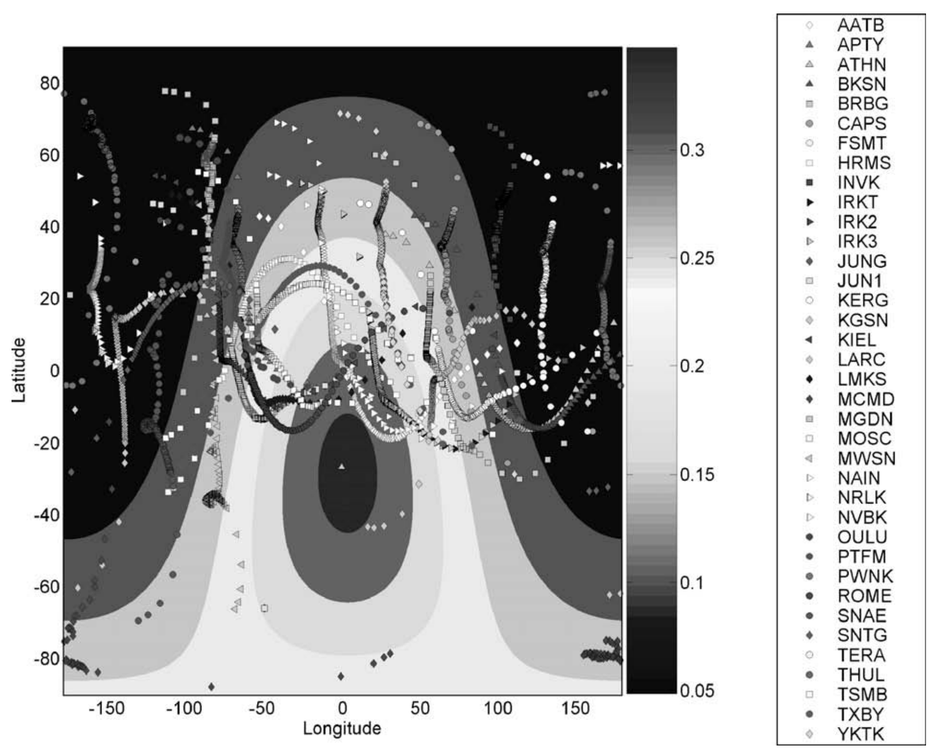

Fig. 3. Contour plot of equal fluxes of solar energetic particle of rigidity greater that 1 GV on 13 December 2006 at 3:05 UT. The unit of the gray scale code is pfu.

tions far from the anisotropic source (e.g. Tixie Bay) recorded smaller increases at that moment. It should be pointed out, however, that during later phases of the event, the results of the NM-BANGLE model application, showed that the narrow particle beam was getting wider with time and consequently more and more NM stations could sense the solar particle event (Plainaki et al., in press).

4. Conclusions

The neutron monitors asymptotic directions of viewing were calculated applying the Tsyganenko 1989 magnetospheric field model for the time period of the solar extreme event of 13 December 2006 (GLE70). From the current analysis, the following main points are revealed:

- On 13 December 2006, neutron monitors around the world had different asymptotic cones recording cosmic rays which came in general from different parts of the sky.
- Due to their different cut-off rigidities as well as to their different asymptotic cones, the neutron monitors of the worldwide network recorded the GLE with different intensity. The enhancement was recorded bigger at sub-polar stations.
- The neutron monitors asymptotic directions of viewing obtained on the basis of Tsyganenko 1989 in combination with the NM-BANGLE model give possible analytical explanations to differences between neutron monitors recordings during GLE70.

Concluding, the importance of the existence of a worldwide network of neutron monitors in studying solar proton events recorded at ground level, should be emphasized. Moreover real-time technology provides such a network with the capability of continuous cosmic ray recordings as well as real-time calculation and on line distribution of the values of several primary proton flux parameters by applying suitable models.

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References

Bieber, J.W., Clem, J., Evenson, P., et al. Relativistic solar neutrons and protons on 28 October 2003, Geophys. Res. Lett., 32, 3, CiteID L03S02, 2005.

Eroshenko, E., Belov, A., Mavromichalaki, H., et al. ‘Cosmic ray variations during the two great bursts of solar activity in the 23rd solar cycle’. Solar Phys. 224, 345–358, 2004.

Fairfield, D.H. A statistical determination of the shape and position of the geomagnetic neutral sheet. J. Geophys. Res. 85, 775–780, 1980.

Gosling, J.T., McComas, D.J., Thomsen, et al. The warped neutral sheet and plasma sheet in the near-Earth geomagnetic tail. J. Geophys. Res. 91, 7093–7099, 1986.

Kudela, K., Bučík, R., Bobík, P. On transmissivity of low energy cosmic rays in disturbed magnetosphere. J. Adv. Space Res. 42 (7), 1300–1306, 2008.

Mavromichalaki, H., Plainaki, C., Gerontidou, M., Sarlanis, C., Souvatzoglou, G., Mariatos, G., Belov, A., Eroshenko, E., Klepach, E., Yanke, V. GLEs as a warning tool for radiation effects on electronics and systems: a new Alert System based on real-time Neutron Monitors. IEEE TNS 54 4, 1082–1088, 2007.

McCracken, K.G., Rao, V.R., Shea, M.A. The Trajectories of Cosmic Rays in a High Degree Simulation of the Geomagnetic Field, Technical Report, 77, Massachusetts Institute of Technology, Cambridge, MA, USA, 1962.

McCracken, K.G., Rao, U.R., Fowler, B.C., Shea, M.A., Smart, D.F. Cosmic ray tables (asymptotic directions, etc.). Annals of the IQSY 1, vol. 14. MIT Press, Cambridge, MA, USA, pp. 198–214, 1968.

Plainaki, C., Belov, A., Eroshenko, E., Kurt, V., Mavromichalaki, H., Yanke, V. Unexpected burst of solar activity recorded by neutron monitors during October–November 2003. Adv. Space Res. 35, 691–696, 2005.

Plainaki, C., Belov, A., Eroshenko, E., Mavromichalaki, H., Yanke, V. Modeling ground level enhancements: the event of 20 January 2005. J. Geophys. Res. Space Phys. 112, A04102, doi:10.1029/2006JA011926, 2007.

Plainaki, C., Mavromichalaki, H., Belov, A., Eroshenko, E., Yanke, V. Application of the NM-BANGLE model to GLE70, in: Proc. 30th Int. Cosmic Ray Conf., Merida, in press.

Ralston, A., Wilf, S.H. Mathematical Methods for Digital Computers. John Wiley and Sons, New York, NY, USA, 1960.

Russell, C.T., Brody, K.I. Some remarks on the position and shape of neutral sheet. J. Geophys. Res. 72, 6104–6106, 1967.

Shea, M.A., Smart, D.F., McCracken, K.G. A study of vertical cut off rigidities using sixth degree simulations of the geomagnetic field. J. Geophys. Res. 70, 4117–4130, 1965.

Smart, D.F., Shea, M.A., Flückiger, E.O. Magnetospheric models and trajectory computations. Space Sci. Rev. 93 (1), 305–333, 2000.

Tsyganenko, N.A. Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels. Planet. Space Sci. 35, 1347–1358, 1987.

Tsyganenko, N.A. A magnetospheric magnetic field model with the warped tail current sheet. Planet. Space Sci. 37, 5–20, 1989.