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The Cosmic Ray Asymptotic Directions for Station Oulu in the Magnetic Field of the Tsyganenko 1989 Model

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Abstract

Using the magnetospheric field model developed by Tsyganenko (1989) the asymptotic directions were calculated for cosmic ray particles entering the top of the atmosphere at Oulu (65.°06N, 25.°47E). The calculations were made for 17^h UT 23.06.1990 at summer solstice when the angle between the Earth's geomagnetic axis and the line perpendicular to the ecliptic plane reaches a maximum value of 34.7°. Different geomagnetic disturbance levels were selected characterized by $\boldsymbol{K_p}$*-index values from 0 to >5–. The cosmic ray asymptotic directions were obtained for azimuth directions corresponding to north, east, south and west, and for different zenith angles (from 0° to 48°). The analyses show that the asymptotic directions of cosmic ray particles with rigidities below 1 GV strongly depend on the disturbance level of the magnetosphere. The asymptotic directions of particles with these rigidities are concentrated within a narrow band along the curves the position of which depend on the* $\boldsymbol{K_p}$*-value and are independent of zenith or azimuth angles. It is also shown that upper cutoff rigidities of cosmic rays decrease with increasing geomagnetic disturbance level.*

Key words: cosmic rays, magnetospheric magnetic field, asymptotic directions, geomagnetic disturbance level

1. Introduction

To study variations of primary cosmic rays it is necessary to take into account influence of the magnetosphere on cosmic ray fluxes. The count rates of primary cosmic rays detected on the Earth's surface depend in particular on the asymptotic cone of acceptance, i.e. on the location of the entrance window for particles outside the influence of the geomagnetic field. The magnetic field of the Earth's magnetosphere and its structure determine the character of the cosmic ray intensity distribution on the Earth's surface and in the near space, and its time variations lead to changes in cosmic ray asymptotic directions and cosmic ray cutoff rigidities. Calculations show that cosmic ray cutoff rigidities decrease with increasing geomagnetic disturbance level (*Danilova and Tyasto*, 1984, 1988, 1996). Low energy cosmic rays and energetic particle measurements near the Earth show that external sources of the geomagnetic field are highly variable and influenced by the disturbances in the outer magnetosphere and the interplanetary space. For example, changes in cutoff location of up to ≈ 5° in latitude in less than one day have been observed, even during periods of only moderate geomagnetic disturbances (*Leske et al.,* 1997).

Variations of cutoff rigidities at high latitudes can have significant effects on manned space stations by increasing the radiation hazard for both the station personnel and sensitive equipment. Lowering of the cutoff rigidities allows the penetration of particles with lower energies to high latitudes and thus increase the radiation locally. Shifting of the cutoff location towards lower latitudes increases the length of time a station stays in polar regions. The risk is evident especially during solar energetic particle events (*Leske et al.,* 1997).

The aim of this work is to study upper cutoff rigidities and asymptotic directions of cosmic rays traversing the magnetosphere and entering the top of the atmosphere (20 km above the surface of the Earth) at Oulu during different levels of geomagnetic disturbances.

2. *Model and method*

Asymptotic directions of cosmic ray particles were calculated using the trajectory-tracing method applying numerical integration of the equation

$$\ddot{\mathbf{R}} = \frac{e}{mc}\dot{\mathbf{R}}\times\mathbf{B}$$

of motion of a particle with charge '*e*' and mass '*m*' in a magnetic field **B**. The Gill modification of the Runge-Kutta iteration method, as adapted by *McCracken et al.* (1962), was applied. This is the standard method of tracing cosmic-ray trajectories and is successfully used in a variety of researches of this type (see e.g. *McCracken et al.,* 1962, *Shea and Smart,* 1975, *Shea et al.,* 1976, *Danilova* and *Tyasto,* 1984, 1988, 1996 and references therein).

The magnetospheric magnetic field **B** is usually represented as a sum of magnetic fields from internal and external sources $\mathbf{B}=\mathbf{B}_i+\mathbf{B}_e$. The magnetic field of internal sources is described by International Geomagnetic Reference Field (IGRF) models (IAGA News, 1991). The IGRF represents the main geomagnetic field and its secular variation as a spherical harmonic series with the coefficients g_n^m, h_n^m. The geomagnetic field potential is

$$V = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left[g_n^m \cos m\varphi + h_n^m \sin m\varphi\right] P_n^m\left(\cos\lambda\right),$$

where a is the mean radius of the Earth (6371.2 km), r is the radial distance from the Earth's center, φ is the longitude from Greenwich, λ is the colatitude and $P_n^m(\cos\lambda)$ are the normalized associated Legendre polynomials. The geomagnetic field components are determined as derivatives $\frac{\partial V}{\partial x}$, $\frac{\partial V}{\partial y}$, $\frac{\partial V}{\partial z}$ (*Chapman and Bartels*, 1940).

In this work the internal magnetic field ($\mathbf{B}_i$) is represented by IGRF with the IAGA90 coefficients up to n = 10 for the epoch 1990 (IAGA News, 1991).

The magnetic field of external sources $\mathbf{B}_e$ is represented by the Tsyganenko (Ts89) model (*Tsyganenko,* 1989) which takes into account the main magnetospheric current systems such as: ring currents, magnetopause currents and the magnetosphere tail currents. The Ts89 model is the third version of magnetospheric magnetic field models developed by the same author (see *Tsyganenko and Usmanov,* 1982, *Tsyganenko,* 1987). In this model vector averages of the magnetospheric field measured during the period from 1966 to 1980 aboard eight IMP and two HEOS satellites were used. The model takes into account the magnetospheric field dependence on the disturbance level characterized by the $\boldsymbol{K_p}$-index as well as seasonal changes of the tilt angle of the geomagnetic dipole axis with respect to the normal to the ecliptic plane.

The ring current and the tail current of the model form a sheet-like system in the near nightside magnetosphere with an arch-shaped configuration of the current flow lines. Near the Earth the current sheet nearly coincides with the dipole equatorial plane and gradually diverges from it at larger distances. It approaches asymptotically a plane parallel to that of the solar magnetospheric equator. The effects of day-night asymmetry are also incorporated in the ring current model by introducing the dependence of the current sheet thickness on the distance X_{sm} along the Sun–Earth line as in the tail sheet model. The current sheet is thicker towards the dayside and towards the flanks of the tail and the asymmetry between the dayside and nightside sectors increases with increasing $\boldsymbol{K_p}$.

The Ts89 model gives a more depressed field in the near magnetotail region in comparison with the previous models by Tsyganenko Ts82 (*Tsyganenko* and *Usmanov*, 1982) and Ts87 (*Tsyganenko*, 1987) for all $\boldsymbol{K_p}$-intervals under consideration, the most dramatic changes being observed for the highest level of disturbances ($\boldsymbol{K_p}$>5–).

3. Results and discussions

The asymptotic directions of the cosmic ray particles, i.e. the particle coordinates on the sphere with radius equal to 25 Earth radii, were calculated for particles entering Oulu with zenith angles ZE=0°, 8°, 16°, 24°, 32°, 40° and 48° and with azimuth angles AZ=0°, 90°, 180°, 270° (north, east, south, west). The particle rigidities ranged from 750 GV down to upper cutoff rigidity (*Cooke et al.,* 1991).

The results were obtained for $\boldsymbol{K_p}$=0, 2, 3 and $\boldsymbol{K_p}$>5– and for the maximum tilt angle of the geomagnetic dipole axis with respect to the normal to the ecliptic plane

ψ=34°.7 corresponding to the position of the Earth in its orbit at summer solstice (for 17^h UT 23.06.1990).

In Fig. 1 the asymptotic directions are shown for cosmic rays arriving with AZ=0° and ZE=0°, 16°, 32° and 48° for three disturbance levels K_p=0, K_p=3 and K_p>5– . Fig. 2 shows the asymptotic directions of particles entering with azimuth angles AZ=0°, 90°, 180°, 270° and with zenith angles ZE=16° for K_p=0, K_p=3 and K_p>5–. The underlined numbers in the figures show the particle rigidities in GV.

It is seen from Fig. 1 that asymptotic directions for particles with rigidities higher than ~11 GV depend significantly on zenith angles and are independent of the K_p-value. It means that high energy particles "remember" their original directions as could be expected. The seemingly large differences in asymptotic longitudes of high energy particles (rigidity 750 GV) with zenith angles 0° and 16° compared to particles with zenith angles 32° and 48° is explained as follows: With increasing zenith angle a value is encountered (about 25° for Oulu latitude) after which particles begin to come over the pole and the longitude changes by 180°. This is more clearly seen from Fig. 3 in which the same results as in Fig. 1 for K_p=0 are presented as entry points of particles on a sphere with radius of 25 Earth radii.

Regions from where 5-10 GV particles can penetrate to the surface at Oulu occupy ~30°in latitude and ~30° in longitude in the northern hemisphere and change insignificantly with increasing K_p-levels for zenith and azimuth angles under consideration (see Fig. 1 and Fig. 2).

From Figures 1 and 2 it can be seen that the curves connecting the asymptotic directions are grouped nearly into one curve for rigidities below 1 GV and that they are slightly different in the 1–5 GV rigidity range. The shape of the asymptotic direction curves depends on the geomagnetic field disturbance level. With increasing K_p-level the asymptotic direction curves become more complex. For example, for K_p=3 it is obvious that for low rigidities a loop structure of the asymptotic directions can be seen shifting in longitude and increasing its radius with increasing disturbance level K_p.

It is obvious that there is a tendency for a decrease of the rigidity limit for accepted particles with increasing K_p.

The effective cutoff rigidity at Oulu in the main geomagnetic field equals 0.78 GV. The figures at the ends of the asymptotic direction curves of Fig. 1 and Fig. 2 show the upper cutoff rigidities which are 0.69-0.72 GV for K_p=0, 0.55-0.56 GV for K_p=3 and 0.35-0.36 for K_p>5-. The atmospheric cutoff rigidity is 1 GV. Thus particles with rigidities lower than 1 GV and higher than at least the upper cutoff rigidities can access the top of the atmosphere at Oulu. Low energy particles can come to Oulu from low, middle and even high south latitudes if K_p=0 and when K_p=3 or K_p>5- they can come from high south latitudes to middle north latitudes in a rather limited longitudinal interval.

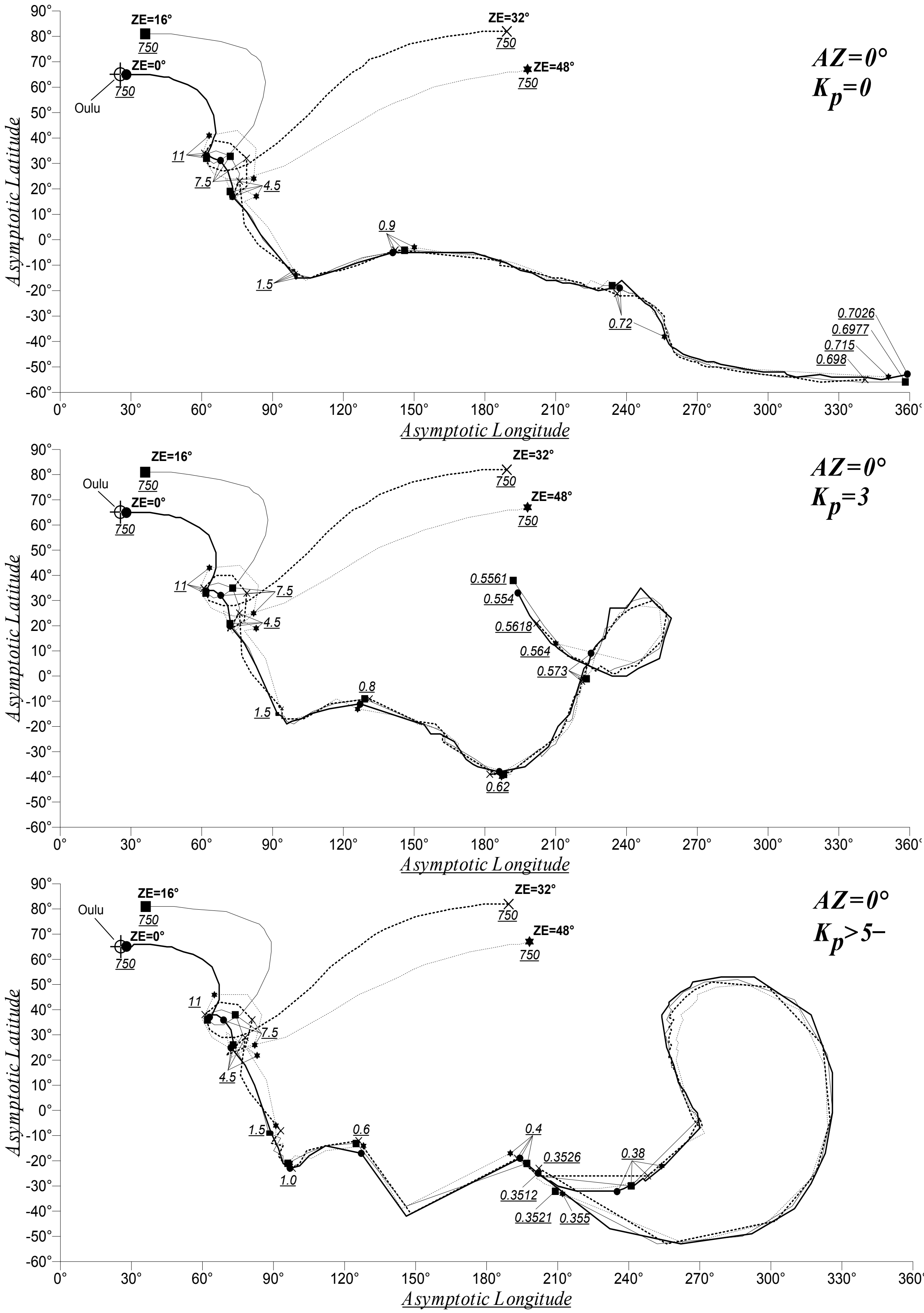

Fig. 1. Asymptotic directions of cosmic ray particles entering Oulu from the north (AZ=0°) at the zenith angles ZE=0°, 16°, 32° and 48° for K_p values 0, 3 and >5-. Underlined figures show particle rigidities in GV.

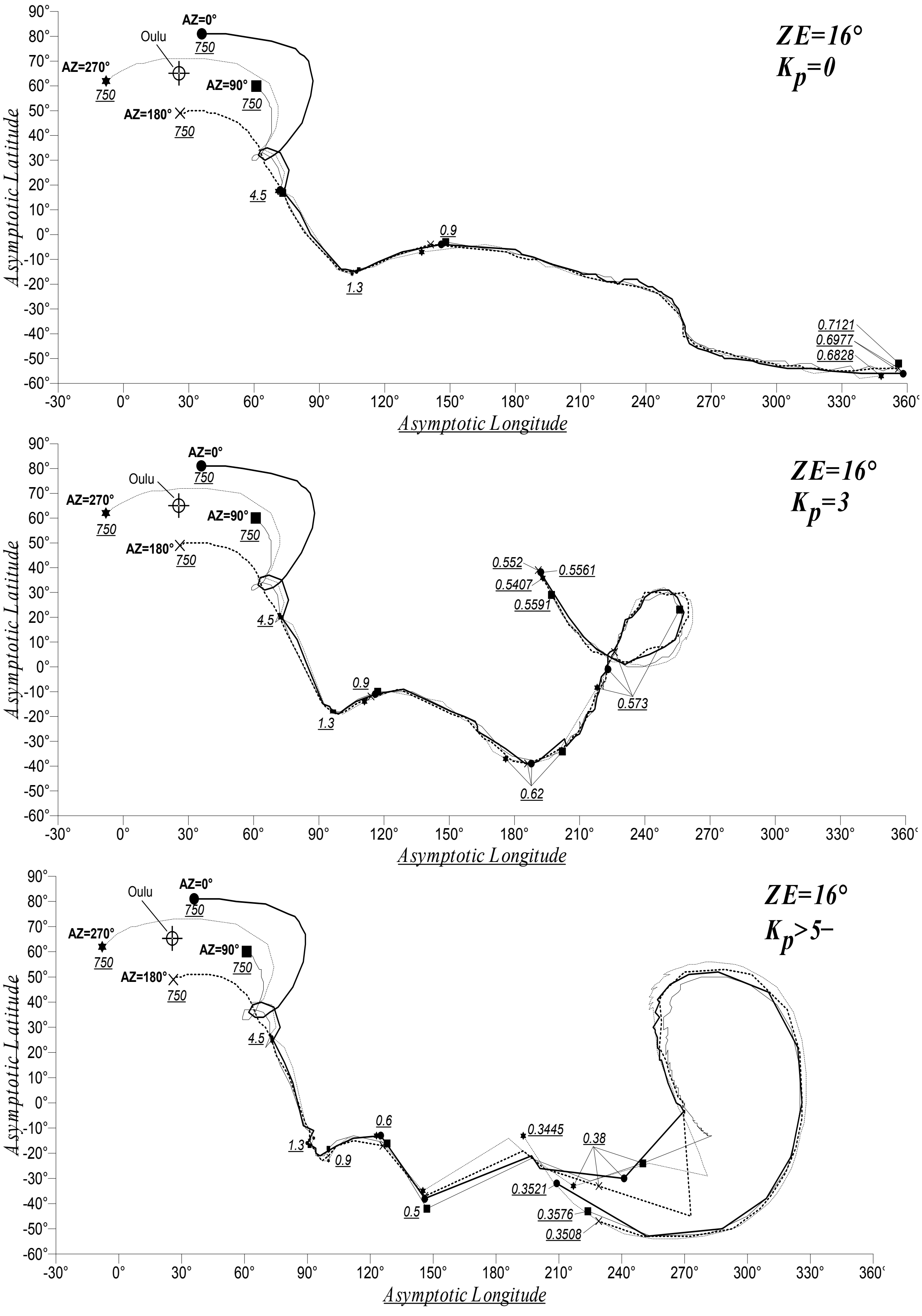

Fig. 2. Asymptotic directions of cosmic ray particles entering Oulu at the zenith angle ZE=16° from the north (AZ=0°), east (AZ=90°), south (AZ=180°) and west (AZ=270°) for $\boldsymbol{K_p}$ values 0, 3 and >5-. Underlined figures show particle rigidities in GV.

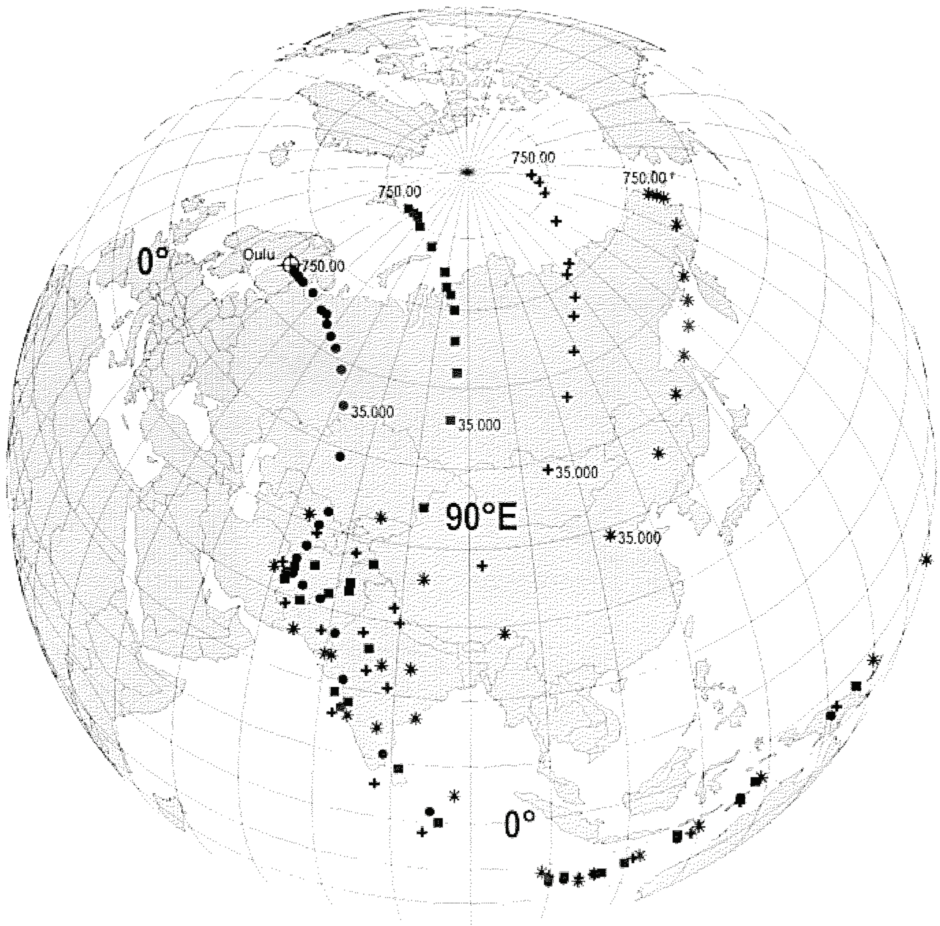

Fig. 3. Asymptotic directions of cosmic ray particles entering Oulu from the north (AZ=0°) at zenith angles ZE=0° (●), 16° (■), 32° (+) and 48° (®) for K_p =0 shown as entry points of particles on a sphere with radius of 25 Earth radii.

3. Conclusions

The Earth's magnetic field restricts the viewing of cosmic ray stations to a cone of acceptance that is energy dependent and turn ground based cosmic ray detectors into directional instruments. Therefore, the asymptotic cone of acceptance must be considered e.g. when differential energy spectrum, anisotropy and direction of relativistic solar protons are studied.

The influence of the geomagnetic field disturbance level on cosmic ray asymptotic directions is seen at particle rigidities less than 5 GV. Due to atmospheric cutoff ground based neutron monitors at high latitudes record particles with rigidities above 1GV. The effect of asymptotic cone of acceptance at these rigidities is demonstrated for instance in the responses of closely spaced neutron monitor stations Apatity and Oulu during highly anisotropic solar particle events of 7 May 1978 (*Shea* and *Smart,* 1982) and 29 September 1989 (*Vashenyuk et al.,* 1997).

Asymptotic directions of particles with rigidities below 1 GV with different azimuth and zenith angles form a narrow band with position and shape depending strongly on the level of the geomagnetic activity. These particles are important in balloon and satellite measurements.

The calculations were performed for a special time of the day (17^h UT), day of the year (June 23) and epoch (1990). It is therefore evident that daily and yearly variations of asymptotic directions will also be present and have to be included in the calculations.

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