Geof. Int. Vol. 20-2, 1981, pp. 121-128

THE TILT EFFECT ON CUTOFF

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(Received: July 22, 1981)

RESUMEN

En este trabajo se analiza el efecto que tiene sobre la rigidez umbral de los protones de rayos cósmicos la inclinación del dipolo magnético respecto al flujo del viento solar. El análisis se hace para diferentes horas locales de arribo vertical a College Station, que tiene una latitud invariante de $\approx 64^{\circ}$. Se encuentra que la energía umbral calculada para diferentes ángulos de inclinación a la misma hora de llegada difiere en más de 20 MeV, correspondiendo las mayores diferencias a la llegada a 18 horas locales y las menores a las 6 horas. También se calcula la variación diurna del umbral tomando en cuenta la variación diurna del ángulo de inclinación, durante los solsticios de verano e invierno para una estación con $\lambda_{inv} = 64^{\circ}$ y una $\phi_{mag} = 0^{\circ}$. Se compara con la variación diurna que se obtiene sin tomar en cuenta las variaciones de este ángulo y se encuentra que existen diferencias mayores de 10 MeV en las energías umbral esperadas.

ABSTRACT

The effect that the tilt of the magnetic dipole with respect to the solar wind flow has on the cutoff energy cosmic ray protons is analysed for different local times of vertical arrival. For the study College Station, with an invariant latitude $\approx 64^{\circ}$, was selected. It was found that the computed cutoff energies for different tilt angles may differ by more than 20 MeV at the same time of arrival. The greatest differences were found at 18H of local time and the smallest at 6H. The diurnal variation of the cutoff, taking into account the diurnal variation of the tilt, was also calculated during winter and summer solstices for a station with $\lambda_{inv} = 64^{\circ}$ and $\phi_{mag} = 0^{\circ}$ and compared with the diurnal variation for zero tilt. Differences higher than 10 MeV were found.

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INTRODUCTION

The problem of cutoff is an old problem. Soon after the discovery of cosmic rays one of the challenges of the new science was to get good theoretical predictions of cutoff energies for protons arriving to a given point and even now it is not an entirely solved problem. Many people have studied the cutoff (see for example: Taylor, 1967; Hoffman and Sauer, 1968; Gall *et al.*, 1968; Smart *et al.*, 1969; Flindt, 1970; Paulikas *et al.*, 1970; Burch, 1971; Imhof *et al.*, 1971) and many things about it are now clear, namely its dependence on the direction of arrival, its dependence on the local time and its dependence on the degree of perturbation of the geomagnetic field. But nevertheless, even taking into account all these factors, the observed cutoff energies are still considerably different from the expected ones (see for example Freier *et al.*, 1959; Lanzerotti, 1968; Ney *et al.*, 1959; Reid and Leinback, 1959; Bailey, 1964; Stone, 1964; Quenby, 1969; Masley *et al.*, 1971; Mc Diarmid *et al.*, 1971).

The main problem when dealing with particles near cutoff is its great sensibility, due to its low energy, to the spatial and temporal variations of the geomagnetic field. In the present work, the variations expected in cutoff energies as a consequence of the changes in the magnetospheric configurations induced by the different tilt angles that the geomagnetic dipole axis forms with the solar wind flux as the time goes by, is analysed and the expected daily variation of the cutoff is calculated, taking into account the diurnal precession of the geomagnetic axis around the geographic axis. Pfitzer (1979), working with the Olson-Pfitzer (1974) model for the magnetospheric field*, states that this model predicts a negligible tilt dependence of the cutoff (he even considers it as not existent) but he does not find a very good verification of this prediction by the experimental data. He argued that the disagreement is due to the use of Kp index in the organization of data, for it is not a good index for representation of the geomagnetic activity. So as the experimental information is not conclusive in the sense of an absence of tilt effect on cutoff a looking for such an effect is intented in this paper with a different model of the magnetosphere.

The analysis here is made for College station at Alaska ($\lambda_g = 64.85^o$, $\varphi_g = 212.10^o$; $\lambda_{inv} = 64.4^o$) having an internal cutoff of 150 MeV. The study was made by computing proton trajectories at four local hours (0H, 6H, 12H, 18H) for vertical arrival, with five different tilt angles: 0^o, $\pm 20^o$ and $\pm 35^o$. The computations were made by numerical integration of the equation of motion of the particles in a mathematical model of the geomagnetic field. The model used was a combination of the Mead and Fairfield (1972) model with coefficients corrected by Hedgecock (1977) (see

* unfortunately not available.

Appendix) and a gaussian expansion of the internal field, using the IGRF coefficients computed by Cain *et al.* (1967). The criteria used in the determination of the cutoff were the following:

1) Computations of trajectories were carried up to a spherical boundary centered at the Earth with a radius of 11 R_E.

2) The maximum number of steps of integration used was 20,000.

3) The calculations were made going down in rigidities by an amount of 0.01 GV each time.

4) When two successive trajectories fail in reach the boundary with 20,000 steps of integration, the one before these two was considered the cutoff.

Cutoff Energies for Different Tilt at the Same Local Hour

It is known that the field lines configuration of the magnetosphere changes considerably when the tilt angle changes (see Figure 1) so one can expect such changes to have some effect on the determination of the minimum energy that a proton must have in order to reach a given point on the earth.

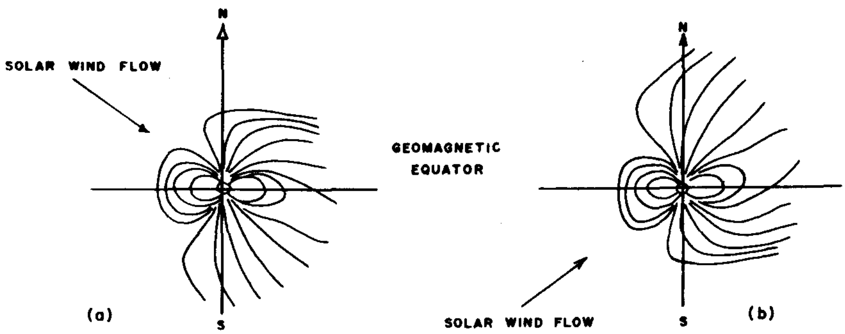

Fig. 1. Mead and Fairfield model lines for different values of the tilt angle: a) Tilt = 35° and b) Tilt = -35°.

Following the method described above the cutoff energies for different local times of arrival were calculated with different values for the tilt angle in the Mead and Fairfiled (1972) model. The results are shown in figure (2). From this figure one can see that the difference can be very large, higher than 20 MeV. In figure (3) the maximum differences observed in cutoff energy for different local hours are plotted. One can see that the differences are maximum at 18H and minimum at 6H.

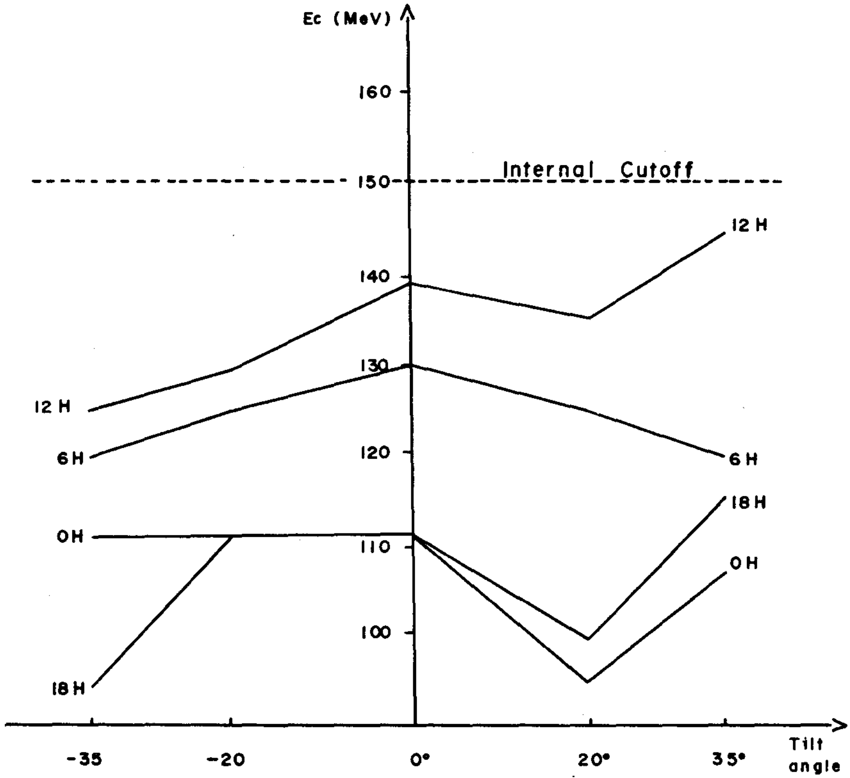

Fig. 2. Computed cutoff energies for College Station at four different local magnetic times of arrival for different values of the tilt angle. The dashed line corresponds to the internal cutoff.

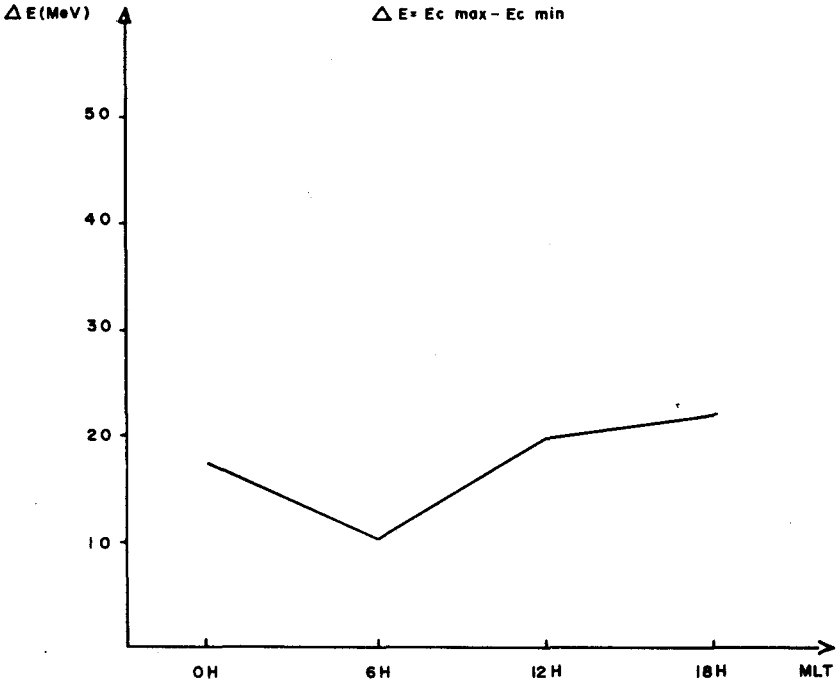

Fig. 3. Maximum changes with the tilt of the computed cutoff energies for a given local magnetic time of arrival at College Station.

The Daily Variation of Cutoff Taking into Account the Daily Variation of Tilt

From the previous results one can conclude that the tilt angle does play an important role in the determination of cutoff, and then it becomes interesting to see how much the daily variation of the cutoff is expected to change when we consider also the daily variation of the tilt. Indeed we know that the tilt angle changes - as much as 23° - during the day due to the precession of the geomagnetic axis around the geographic axis. Such changes in the tilt induce a continuous deformation on the magnetospheric field lines configuration that have been experimentally observed from HEOS 2 data (Thomas, 1978) and so, the daily variation of cutoff energy is indeed determined by changes in the geomagnetic configuration due to two different effects: the changes of the local hour and the change of the tilt angle during the day. Taking into account both of them the expected daily variation of cutoff was obtained for the two extreme cases of daily variation of tilt values - winter and summer solstices - when tilt angle varies along the day from 12° to 35° for summer, and from -35° to -12° for winter. In figure (4) the curves corresponding to a point on the 0° magnetic meridian with an invariant latitude of ≈ 64° are shown. This point was chosen because it is expected to behave as College Station but the tilt corresponding to each local hour is easier to look at. For each point in the curves two parameters were taken into account; the local hour and the geomagnetic tilt at that hour. In the same figure the curve obtained when considering a zero tilt all through the day is also drawn for comparisson. The data for the construction of Fig. (4) were taken from figure (2). As can be seen from figure (4), the expected tilt effect in the daily variation of the cutoff is much stronger in winter than in summer. This is not really surprising because from figure (1) we can see that a larger deformation of the geomagnetic field (respect to the 0° tilt configuration) is expected in the north hemisphere for negative tilt angles (Fig. 1b), which is the case for winter. The inverse situation (stronger effect in summer) is expected in the south hemisphere.

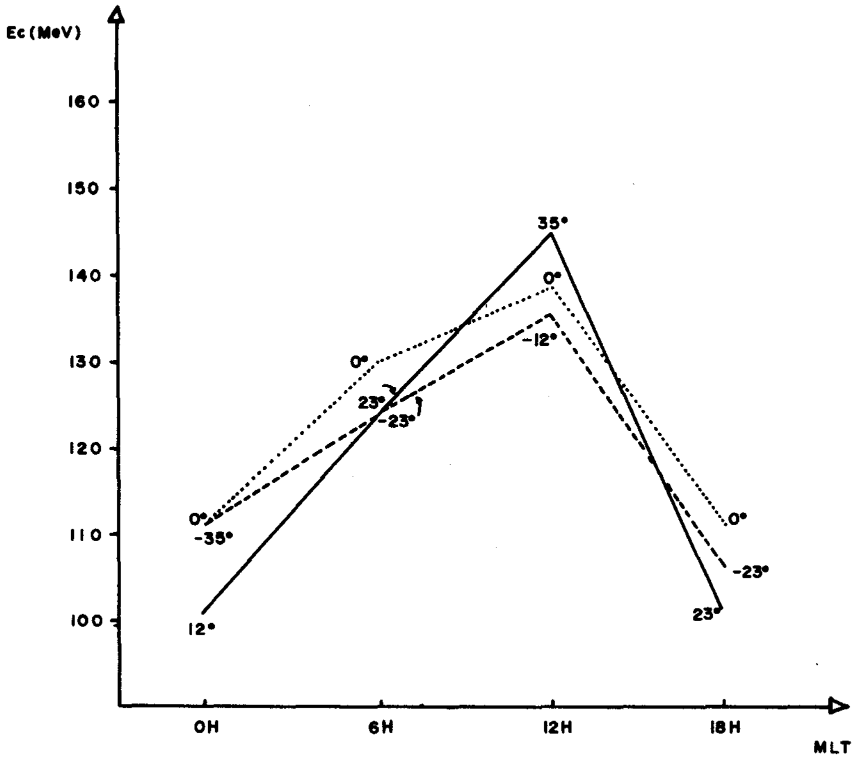

Fig. 4. Daily variation of the cutoff energy at a point in the north hemisphere with $\lambda_{inv} \approx 64^{\circ}$ located in the 0° geomagnetic meridian for two extreme cases: summer solstice (solid line) and winter solstice (dashed line). The daily variation expected for zero tilt is also shown (pointed line). The corresponding values of the tilt for 0H, 6H, 12H and 18H are shown in each case along the curves. The tilt value of 23° corresponds to 6H in summer and that of -23° to 6H in winter.

CONCLUSION

The present study shows that changes in the tilt angle produce significative changes in the expected cutoff for vertical arrival at a station with an invariant latitude about 64^{o}, that is not really very high. From figure (1) one can expect even a larger effect at higher latitudes. So even though the cutoff calculated here may not be very accurate (due to the low value of the maximum number of steps of integration used in their computation) we certainly can conclude from this study that tilt angle and its temporal variations, not only along the year, but even along the day, are factors that largely "affect" the minimum energy of the particles that are able to reach a given point in the magnetosphere, at least at invariant latitudes above 64^{o}.

APPENDIX

Mead and Fairfield Model for the Geomagnetic Field with Hedgecock's Coefficients

$$B_x = 18.733\,z + 4.388\,xz + G\,(3.843 - 3.205\,x - 0.965\,x^2 - 0.821\,y^2 \quad 1.303\,z^2)$$

$$B_y = 5.267\,yz + G\,(-1.824\,y - 0.495\,xy)$$

$$B_z = 1.809 + 12.484\,x + 6.065\,x^2 + 4.030\,y^2 + 0.440\,z^2 + G\,(5.030\,z + 2.424\,xz)$$

The x, y, z coordinates are solar magnetic, as defined in Mead and Fairfield (1975), and G is the factor for the tilt, also defined in that paper.

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