Magnetosheath Effect and GLE Analysis

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***Abstract*— For the determination of cosmic ray particle propagation inside the Earth's magnetospheric field, usually a combination of the internal magnetic field described by the IGRF model and the external field contribution described by e.g. the Tsyganenko 1989 field model is used. Up to now, however, the effect of the magnetosheath field has not been considered. We combined the magnetosheath magnetic field model proposed by Kobel and Flückiger with the Tsyganenko 1989 model of the magnetospheric magnetic field and implemented it into a trajectory-tracing program. Based on the simulation results for cosmic ray particles arriving at neutron monitor stations, the significance of the magnetosheath effect is shown. The consequences of the magnetosheath field on the results of GLE analysis have been investigated for the relativistic solar particle event on 20 January 2005 and for a hypothetical event for which a pronounced effect could be expected.**

I. INTRODUCTION

For the analysis of GLEs observed by neutron monitors (NM), the asymptotic directions (direction of incidence of cosmic ray particles into the geomagnetosphere) and the geomagnetic cutoff rigidities of the NM stations must be known. These quantities are determined by simulating the trajectories of cosmic ray particles in the geomagnetic field. The magnetospheric magnetic field models generally utilized in near-Earth space include a combination of the internal magnetic field described by the IGRF model [1], [2] and the external field contribution described by e.g. the Tsyganenko 1989 field model [3]. The magnetic field of the magnetosheath, i.e. the magnetic field between the bow shock and the magnetopause, is usually not considered. In order to investigate the significance of this effect, we combined the magnetosheath magnetic field model developed by Kobel and Flückiger [4] with the Tsyganenko 1989 model [3] of the magnetospheric magnetic field and implemented it into a trajectory-tracing program [5].

In this paper we investigate the magnetosheath effect on the determination of the apparent source position and the spectrum of solar cosmic rays from NM data during the large and anisotropic GLE on 20 January 2005. Based on a hypothetical event we then analyse the conditions under which the magnetosheath affect may effect the GLE analysis.

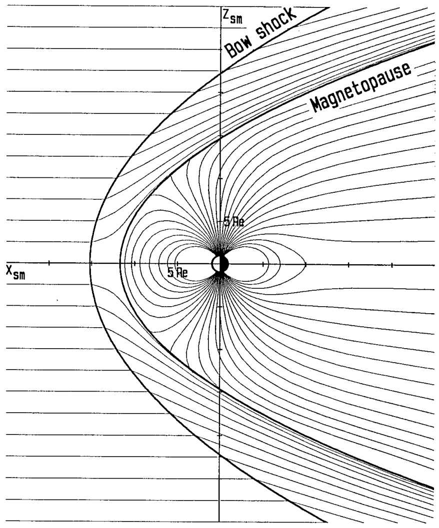

Fig. 1. Field line pattern of the near-Earth magnetic field in the $x_{SM}z_{SM}$-plane of the solar magnetospheric coordinate system for zero dipole tilt, Kp=0, R_{bs}/R_{mp}=1.3, B_{xsm}^{HMF} = 10 nT, $B_{ySM}^{HMF} = B_{zSM}^{HMF}$ = 0 nT.

II. MAGNETOSHEATH EFFECT

The theoretical study of the effect of the magnetosheath magnetic field on charged particle propagation is based on a trajectory tracing computer program utilizing a mathematical description of the near-Earth magnetic field [5]. The steady state magnetic field in the magnetosheath is modeled according to Kobel and Flückiger [4]. There is a total of seven parameters to specify a particular magnetic field configuration: date and time, geomagnetic activity index Kp, the three components of the heliospheric magnetic field (HMF) in the geocentric solar magnetospheric (SM) coordinate system, B_{xSM}^{HMF}, B_{ySM}^{HMF}, B_{zSM}^{HMF}, and the ratio of the stand-off distance of the bow shock to the stand-off distance of the magnetopause, R_{bs}/R_{mp}. The HMF varies in strength near Earth from 1 to $\sim$40 nT, with an average value of $\sim$6 nT [6]. More than 99% of the 5-minute values of IMP-8 measurements have a strength of the HMF $\leq$15 nT. The ratio R_{bs}/R_{mp} depends mainly on the adiabatic constant of the solar wind plasma. In general, this ratio increases from $\sim$1.2 to $\sim$1.5 as the adiabatic

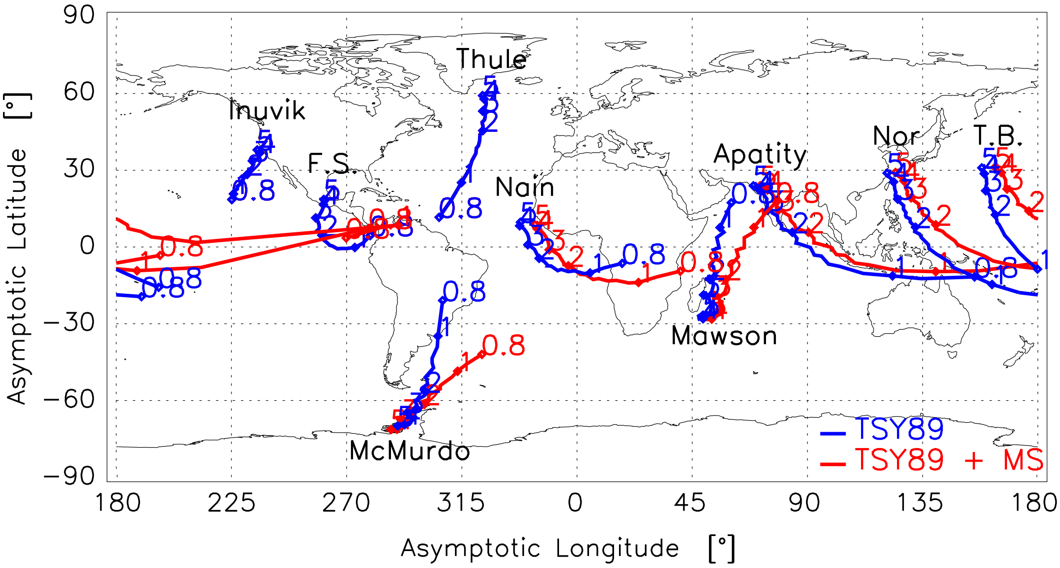

Fig. 2. Asymptotic directions during the main phase of the GLE on 20 January 2005 for selected polar NM stations according to IGRF + Tsyganenko89 model (blue) and according to IGRF + Tsyganenko89 + magnetosheath model (red). The numbers indicate the particle rigidity in GV. NM stations: Apatity, Fort Smith (F.S.), Inuvik, Mawson, McMurdo, Nain, Norilsk (Nor), Thule, Tixie Bay (T.B.).

constant becomes larger. Fig. 1 illustrates a typical topology of the near-Earth magnetic field for the zero dipole tilt angle, Kp=0, R_{bs}/R_{mp}=1.3, and with an HMF parallel to x_{SM}, i.e. $B^{HMF}_{xSM} = 10$ nT, and $B^{HMF}_{ySM} = B^{HMF}_{zSM} = 0$ nT.

To investigate the magnetosheath effect on GLE analysis, the GLE parameters during the big event on 20 January 2005 were determined by using the asymptotic directions as evaluated with and without the magnetosheath effect.

It is obvious that differences in the asymptotic directions occur mainly at low rigidities, and therefore the asymptotic directions are predominantly affected at high latitude NM stations. Fig. 2 shows a world map with the asymptotic directions of vertically incident cosmic ray particles at selected polar NM stations with and without the effect of the magnetosheath during the main phase of the GLE on 20 January 2005. The asymptotic directions are plotted for rigidities from 5 GV down to the main geomagnetic cutoff rigidity or the atmospheric cutoff rigidity respectively. The input parameters of the magnetosheath field model on 20 January 2005 around 0700 UT were defined as follows: As the standoff distances of the bow shock and of the magnetopause are not known from satellite measurements during the entire GLE, we took the value of 1.5 for the ratio R_{bs}/R_{mp} to have a large magnetosheath effect on the asymptotic directions. The observed HMF near Earth differed from the nominal direction and had a pronounced northward direction with $B^{HMF}_{xGEO} = 0.5$ nT, $B^{HMF}_{yGEO} = 1.0$ nT, and $B^{HMF}_{zGEO} = 6.0$ nT. During the main phase of the GLE, the entry points into the geomagnetosphere of the particle trajectories for the NM stations Fort Smith, Inuvik, and Thule are in the magnetotail where the effect of the magnetosheath can not be determined accurately due to the limitations of the model. Therefore for these stations no trajectory calculations were performed in the magnetosheath.

In Fig. 3 the changes in the asymptotic directions due to the effect of the magnetosheath are shown for selected polar NM stations as a function of rigidity. For rigidities greater than 2 GV the change in asymptotic direction due to the magnetosheath effect is less than 10°. Below 2 GV the effect of the magnetosheath increases clearly for all NM stations shown. At rigidities around 1.5 GV where high latitude NMs have the greatest response for a typical solar cosmic ray spectrum, the effect of the magnetosheath causes changes in the asymptotic directions of $\sim$15°. The effect is most pronounced at the NM station Tixie Bay where the changes in asymptotic direction increase strongly to more than 80° at $\lesssim$0.9 GV.

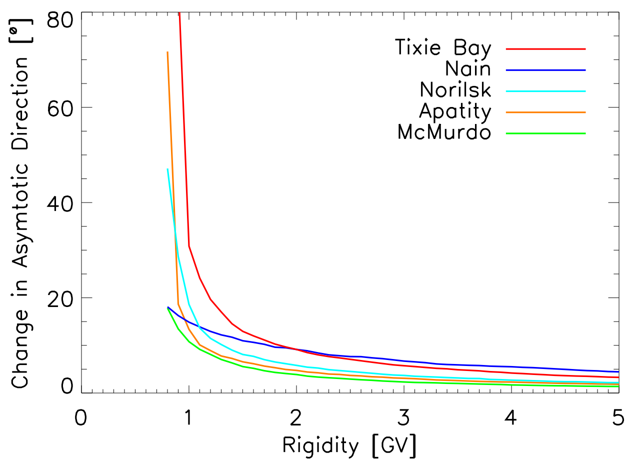

Fig. 3. Changes in asymptotic directions due to the effect of the magnetosheath during the main phase of the GLE on 20 January 2005.

TABLE I

GLE PARAMETERS FOR THE EVENT ON 20 JANUARY 2005 IN THE TIME INTERVAL 0653–0655 UT BASED ON THE DATA OF THE NM STATIONS OF THE SPACESHIP EARTH [9] EVALUATED WITH AND WITHOUT THE MAGNETOSHEATH (MS) EFFECT.

Parameter	without MS	with MS
apparent source geogr. longitude	265°E	265°E
apparent source geogr. latitude	-84°	-84°
spectral index γ	7.7	7.5

III. ANALYSIS OF GLE NEUTRON MONITOR DATA

The effect of the magnetosheath on the determination of the GLE parameters was investigated for the GLE event on 20 January 2005 by using the data of 41 stations of the worldwide NM network. The GLE parameters, i.e. apparent source position, pitch angle distribution, and rigidity spectrum of the solar protons near Earth were deduced according to the method by Smart et al. [7] and Debrunner and Lockwood [8]. For the solar particle spectrum near Earth, a power law dependence on rigidity was adopted:

$$J_{\|}(P,t) = A(t) \cdot P^{-\gamma(t)}$$

Using a trial and error procedure, the GLE parameters can be determined by minimizing the differences between the calculated and the observed NM increases, $\Delta N_{calc}(t)$ and $\Delta N_{obs}(t)$.

As can be seen from Figs. 4 and 5, the analysis during the initial, main, and decay phases of the GLE on 20 January 2005 shows no relevant differences in the GLE parameters with and without consideration of the magnetosheath effect.

To further investigate the influence of the magnetosheath on the GLE analysis, we repeated the determination of the GLE parameters for the time interval 0653–0655 UT during the main phase with and without the magnetosheath effect by using only the NM stations of the Spaceship Earth network [9], i.e. Apatity, Cape Schmidt, Fort Smith, Inuvik, Mawson, McMurdo, Nain, Norilsk, Tixie Bay, and Thule. All these NM stations have a vertical geomagnetic cutoff rigidity <1 GV, and therefore a possible influence of the magnetosheath on the determination of the GLE parameters could be expected when only the data of these NM stations are used for the analysis. The results of this analysis are summarized in Table I. As in the analysis described above when the data of the entire worldwide NM network were used, the obtained values of the GLE parameters again do not show significant differences with and without magnetosheath effect. However, it is noteworthy that the analysis using only the Spaceship Earth data results in a significantly harder spectrum compared to the analysis with the data of the entire worldwide network of NMs.

In a further step we constructed a hypothetical event for which we calculated the relative count rate increase with the magnetosheath effect, ΔN_{calc}^{withMS}, for the NM stations of Spaceship Earth. For these computations we applied the 20 January 2005 GLE parameters for the time interval 0653–0655 UT as obtained in our analysis by using the data of 41 NM stations. The input parameters of the magnetosheath model were also chosen according to this time with the exception of the magnitude of B_{HMF}, which was set to two times the observed value, i.e. $|B_{HMF}| \sim 12$ nT. Then, based on the hypothetical NM data the GLE parameters were determined using the asymptotic directions without the magnetosheath effect. The results of this investigation are summarized in Table II together with the input data that correspond to the GLE parameters as obtained from a GLE analysis considering the magnetosheath effect. The investigation with a stronger magnetosheath magnetic field shows a significant effect of the magnetosheath in the determination of the apparent source position as well as in the spectral index. The change in the apparent source position is $\sim 15°$. Neglecting the magnetosheath effect in the GLE analysis leads to a significantly harder spectrum.

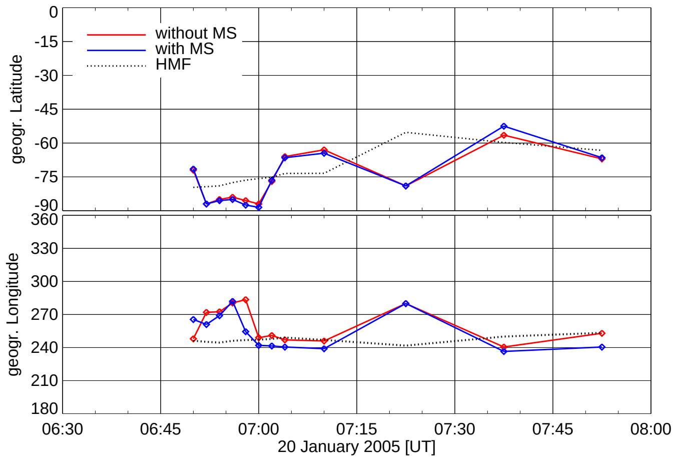

Fig. 4. Apparent source direction of the solar cosmic ray proton flux without (red) and with (blue) magnetosheath effect and observed direction of HMF (dotted lines) vs. time.

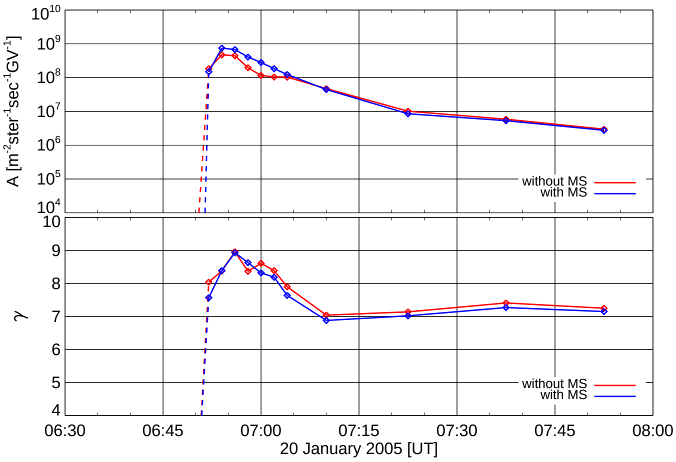

Fig. 5. Parameters of the solar particle rigidity spectrum. Amplitude A (top) and spectral index γ (bottom) for the assumed power law in rigidity vs. time, without (red) and with (blue) magnetosheath effect.

TABLE II

HYPOTHETICAL EVENT. FOR DETAILS SEE THE TEXT.

Parameter	without MS	with MS (= input)
apparent source geogr. longitude	274°E	245°E
apparent source geogr. latitude	-68°	-79°
spectral index γ	4.1	6.0

In Fig. 6 the expected relative count rate increases with the magnetosheath effect of selected polar NM stations are plotted for different $|B_{HMF}|$. For the results shown in this figure with the exception of $|B_{HMF}|$, all other input parameters of the magnetosheath model correspond to the conditions on 20 January 2005, ~0655 UT. The used GLE parameters again correspond to those obtained in our analysis with the data of 41 NM stations for the time interval 0653–0655 UT. $|B_{HMF}| = 0$ nT means that there is no magnetic field in the magnetosheath, i.e. there is a relative count rate increase without the magnetosheath effect. The figure shows clearly that under certain circumstances the magnetosheath can have a pronounced effect on the relative count rate increase of a polar NM station during an anisotropic GLE.

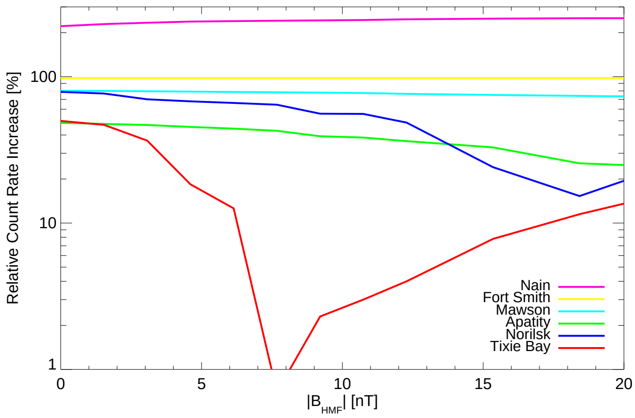

Fig. 6. Expected relative GLE count rate increase for selected NM stations as function of $|B_{HMF}|$. For details see the text.

IV. SUMMARY AND CONCLUSIONS

The effect of the magnetosheath field on the results of GLE analysis have been investigated for the relativistic solar particle event on 20 January 2005 by using the data of the worldwide network of NM stations. For this purpose the magnetosheath magnetic field was included in the trajectory calculations for the determination of the asymptotic directions and of the geomagnetic cutoff rigidity of the NM stations. The magnetic field of the magnetosheath, which itself depends strongly on the strength and the direction of the HMF, can considerably affect the asymptotic directions at individual locations at low rigidities, a fact that might be of importance for highly anisotropic GLEs. However, the determined GLE parameters for the 20 January 2005 event with and without magnetosheath do not differ significantly. The investigation of a hypothetical event revealed that the magnetosheath may have an effect on GLE analysis for highly anisotropic events when the apparent source has a position close to the asymptotic directions of key stations at the rigidity range ~1–2 GV. This is particularly so when only the data of polar NM stations, e.g. Spaceship Earth, are used.

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