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The ground-level enhancement of 14 July 2000: Explaining the difference between near-by neutron monitors at Apatity and Oulu

E. V. Vashenyuk[1], B. B. Gvozdevsky[1], V. V. Phelkin[1], Polar Geophysical Institute, Apatity, Russia[1], I. G. Usoskin[1], K. Mursula[1], and G. A. Kovaltsov[1]

[1]Sodankylä Geophysical Observatory, Oulu unit, University of Oulu, Oulu, Finland
[1]Department of Physical Sciences, University of Oulu, Oulu, Finland
[1]Ioffe Physical-Technical Institute, St. Petersburg, Russia

Abstract. Count rates of two closely located neutron monitors (NMs) at Oulu and Apatity depicted an unusually different behaviour during the onset phase of the ground–level enhancement (GLE) of 14 July 2000. Similar differences were observed during the onsets of GLEs of 2 May 1998 and 15 April 2001. All these three events took place after a strong Forbush decrease, implying significantly disturbed interplanetary and geomagnetic conditions. In all cases the NM with a higher count rate (Oulu on 2 May 1998 and 15 April 2001, Apatity on 14 July 2000) was located in the so-called 14 MLT region (14-16 hours of Magnetic Local Time) where the maximum dayside auroral intensity and some other anomalous geophysical phenomena are located. Here we analyse these events using data from Apatity, Oulu and some other NMs, as well as their asymptotic cones calculated using the Tsyganenko 1989 magnetospheric model. We suggest that there is an anomaly in magnetospheric structure in the 14 MLT sector which facilitates the penetration of cosmic ray protons from the dayside magnetopause to the ground.

1 Introduction

The neutron monitors at Apatity and Oulu are located fairly close to each other, and variations in their count rates are generally roughly equal with only few rare exceptions. An unusually clear difference between the count rates of these two NMs took place during the onset phase of the GLE of 14 July 2000.

The GLE of 14 July 2000 was caused by the parent flare 3B/X5.7 with heliocoordinates N22 W07. The start of type II radioburst, which roughly corresponds to the time of relativistic proton acceleration (Cliver et al., 1982), was registered at 10:20 UT. The GLE occurred during a Forbush decrease, implying significantly disturbed interplanetary and geomagnetic conditions. A bidirectional solar proton anisotropy was observed during the GLE and was related to a loop-like IMF structure during the CME producing the Forbush effect (Richardson et al., 1991, Vashenyuk, 2000). The interplanetary anisotropy of relativistic solar protons will be studied here by means of asymptotic cones of neutron monitor stations.

Similar differences between Apatity and Oulu were observed during the GLEs of 2 May 1998 and 15 April 2001 under similar geomagnetic conditions. In this paper we study these exceptional GLEs, with the main emphasis on the 14 July 2000 event.

Correspondence to: B.B.Gvozdevsky
(gvoy@pgi.kolasc.net.ru)

2 Neutron monitor observations on 14 July 2000

Fig. 1 shows the time profiles of the 14 July 2000 GLE for a number of high-latitude neutron monitors. The profiles at the two closely located stations of Apatity and Oulu are shown in Fig. 1a. A remarkable feature is the initial impulse-like increase of count rate after about 10:30 UT, leading to a high maximum in Apatity and a lower local maximum in Oulu. The two profiles coincide closely for the rest of the GLE event after this initial maximum. Fig. 1b shows the GLE profiles at Apatity and Terre Adelie. The gradual intensity increase at Terre Adelie differs from the fast increase at Apatity and corresponds to a delayed population of solar protons. Note however, that the increases corresponding to the prompt and delayed populations start nearly simultaneously. Fig. 1c shows the profiles of the Thule and Goose Bay NM count rates, and Fig. 1d the Goose Bay and Oulu profiles. One can see that the prompt solar protons were also observed at Thule leading to an even higher and slightly earlier maximum than in Apatity. We also note that the profiles of all the stations are close to each other for later times after ~ 12 UT.

3 Anisotropy effects

Fig. 2 shows the asymptotic cones in GSE coordinates for a

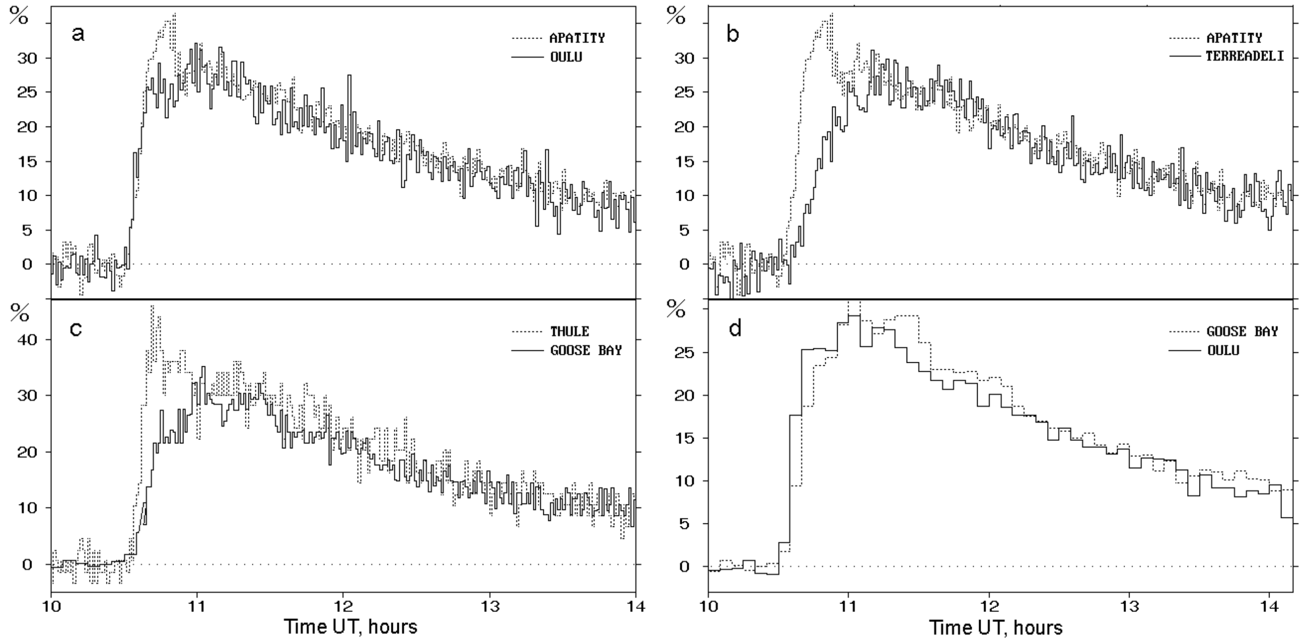

Fig.1. GLE 14 July 2000. Increase profiles at a number of NM station pairs. **a**: Apatity - Oulu; **b**: Apatity - Terre Adelie; **c**: Thule - Goose Bay; **d**: Goose Bay - Oulu. Note the prompt initial peak registered by Thule and Apatity NMs.

number of cosmic ray stations calculated using the Tsyganenko-89 model. The IMF orientation (**x** for anti-sunward; + for sunward) as measured by the ACE spacecraft is shown there, taking into account the 40 min delay due to solar wind propagation from ACE to the Earth. The constant pitch angle lines are drawn in steps of 10^o from 0^o (anti-sunward direct flux) to 180^o (sunward reverse flux). The prompt impulse-like increase was rather anisotropic and was mainly registered by the Thule station which has its entire asymptotic cone inside a region of small ($<40^o$) pitch angles. On the other hand, only the high-rigidity end of the the asymptotic cone of Goose Bay is within the same range of small pitch angles. Therefore this station registered only a fraction of the prompt anisotropic population of the relativistic solar protons, leading to a slower increasing profile and only a low, shoulder-type maximum at the time of the high maximum at Thule.

Most of the Goose Bay asymptotic cone lies in the same pitch angle range (outside 40^o) as Apatity and Oulu. Accordingly, the profiles at Goose Bay and these two stations are rather similar. In particular, Goose Bay is almost identical with Oulu throughout the event (Fig. 1d). However, despite the fact that the asymptotic cones of Apatity and Oulu are very close to each other, there is a clear difference between Apatity on one hand and Oulu and Goose Bay on the other. Only at Apatity the initial anisotropic population formed a clear maximum, in analogy with Thule (Fig. 1a). Note also that the profiles at Apatity and Oulu were identical immediately after this maximum, already since before 11 UT, reflecting the overall similarity at these two near-by stations. On the other hand, some small differences were found even thereafter between the other stations until the anisotropy disappeared and all the profiles were made identical at about 15 UT when another interplanetary shock arrived to the Earth (not shown).

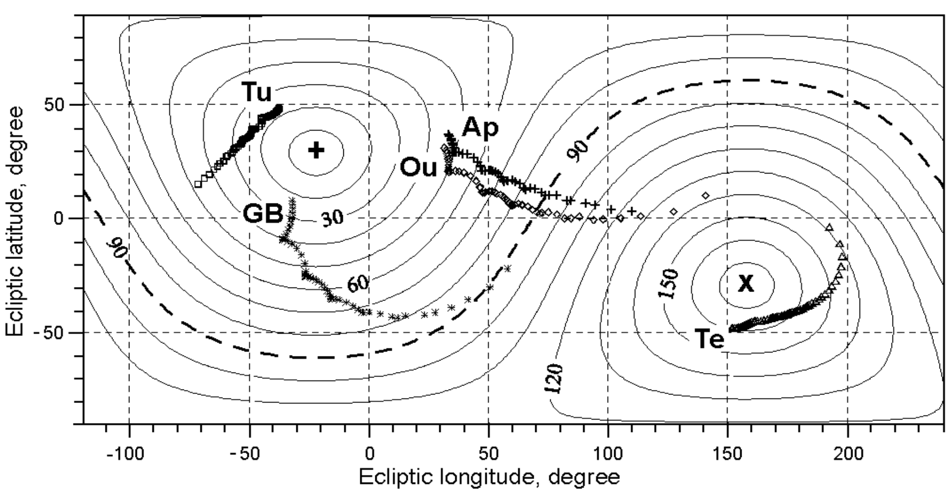

Fig.2. Asymptotic cone map for 11:00 UT, 14.07.2000. NM stations: Thule, Apatity, Oulu, Goose Bay, Terre Adelie. The rigidity range is 1-20 GV. Letter indexes are near the high-rigidity (20 GV) ends. The IMF direction: + (to the Sun) and **x** (from the Sun) and the pitch angle grid from 0^o to 180^o are shown.

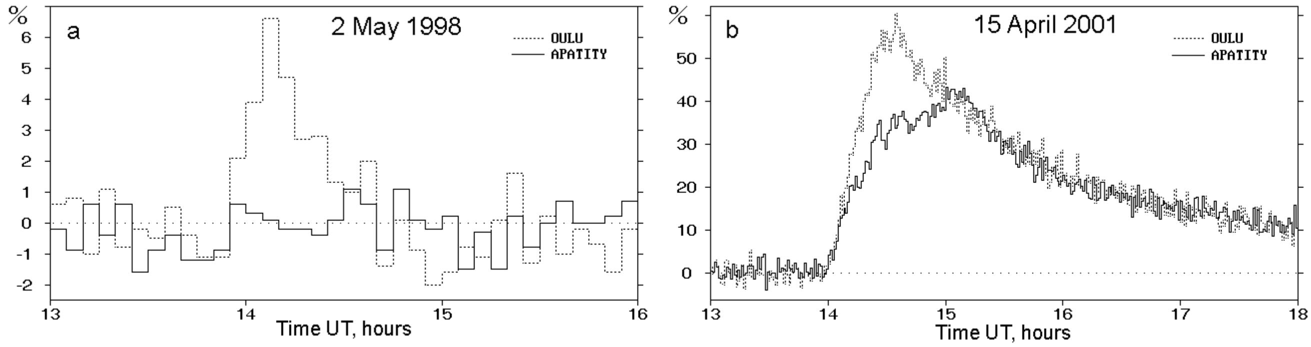

Fig.3. The difference between Apatity and Oulu GLE effect in the events of 2 May 1998 (**a**) and 15 April 2001 (**b**).

4 Other examples of the Apatity-Oulu GLE difference

As long-term observations have shown, Apatity and Oulu neutron monitors demonstrate generally nearly equal increase profiles during GLEs. Only very few occasions with significant differences are known. These cases have been associated in the literature with a strong interplanetary anisotropy. In the 7 May 1978 GLE, the calculated anisotropy axis passed directly through the closely aligned asymptotic cones of Apatity and Oulu. The observed difference was supposed to be due to a difference in the asymptotic direction for equal rigidities between Apatity and Oulu (Shea and Smart, 1982). A similar reason for the difference between Apatity and Oulu was suggested for the 29 September 1989 GLE (Vashenyuk et al., 1997). During the 16 February 1984 GLE, the Apatity-Oulu difference was attributed to a possible drift-like effect of high-energy solar protons in the magnetosphere (Shumilov et al., 1993).

Fig. 3 shows two other cases of a difference between Apatity and Oulu during the GLEs of 2 May 1998 (Belov et al., 2000; Danilova et al., 1999) and 15 April 2001. The initial impulsive increase observed in Oulu and nearly missed by Apatity (Fig. 3a) was attributed by Danilova et al. (1999) to some magnetospheric effect under disturbed conditions. The GLE of 15 April 2001 (Fig. 3b) was caused by a solar flare X14/2B, heliocoordinates S20 W85. The start of the type II radioburst was recorded at 13:48 UT. We note that the pronounced difference between Apatity and Oulu occurs at roughly the same time of day in these two events, as well as during roughly the same period of year implyng for a roughly similar orientation for the geomagnetic dipole tilt. Note also that the difference is observed only for the prompt anisotropic fraction of solar partcles.

5 Discussion

When considering the anisotropy effects during the 14 July 2000 GLE one should keep in mind the probable loop-like IMF structure related to the CME causing the developing Forbush effect. The bidirectional anisotropy may have been created by an injection of energetic solar protons at the two foot-points of the loop in the corona (Richardson et al., 1991). It is also probable that the reverse (sunward) flux observed at Terre Adelie (Fig. 1c) is not the direct (anti-sunward) flux reflected back from the other end of the loop since the direct and the reflected flux started increasing nearly simultaneously. (However, the increase in the sunward flux at Terre Adelie was slower).

As seen in Fig. 1 Thule, owing to its favourable location for low pitch angles, observed by far the fastest increase and the highest maximum during the beginning of GLE. Apatity, Oulu and Goose Bay also observed a fast increase and either a clear maximum (Apatity) or lower shoulder-type local maximum (Oulu, Goose Bay). However, as to the dramatic difference between the near-by Apatity and Oulu stations in the beginning of the event, neither of the earlier explanations offer a satisfactory solution. Instead, we suggest for a new, magnetospheric explanation for this difference. Note first that a common feature for all the three GLE events (14 July 2000, 2 May 1998 and 15 April 2001) is that the two stations were in the day-side local time sector. Moreover, in each case the station detecting the higher increase was inside the so called 14 MLT region (14-16 hours of Magnetic Local Time). This afternoon sector of the magnetosphere is characterised by the maximum occurrence of dayside aurora as well as by some other geophysical anomalies (Kozlovsky and Kangas, 2001 and references therein).

Fig. 4a shows schematically, in the geomagnetic equatorial plane, the position of Apatity and Oulu stations with respect to the 14 MLT sector (shaded in the Figure), their asymptotic cones, and the IMF direction during the 14 July 2000 GLE. Fig. 4b shows the same for the two other special GLE events of 2 May 1998 and 15 April 2001. One can see that in all these three cases the asymptotic cones of Apatity and Oulu are directed mainly in the anti-sunward direction, and would thus, within the framework of the standard magnetospheric model, be unable to observe the anisotropic flux from the Sun. However, since they did observe the flux, this implies a need for dramatic changes in the temporary configuration of the magnetosphere from the average configuration described by the model.

As to the difference between Apatity and Oulu, note that Apatity which registered the higher maximum during the 14 July 2000 GLE was inside the 14 MLT sector, whereas Oulu was outside it. Similarly, during the other two GLEs (2 May 1998 and 15 April 2001) Oulu registered the higher flux and was inside the 14 MLT sector while Apatity was

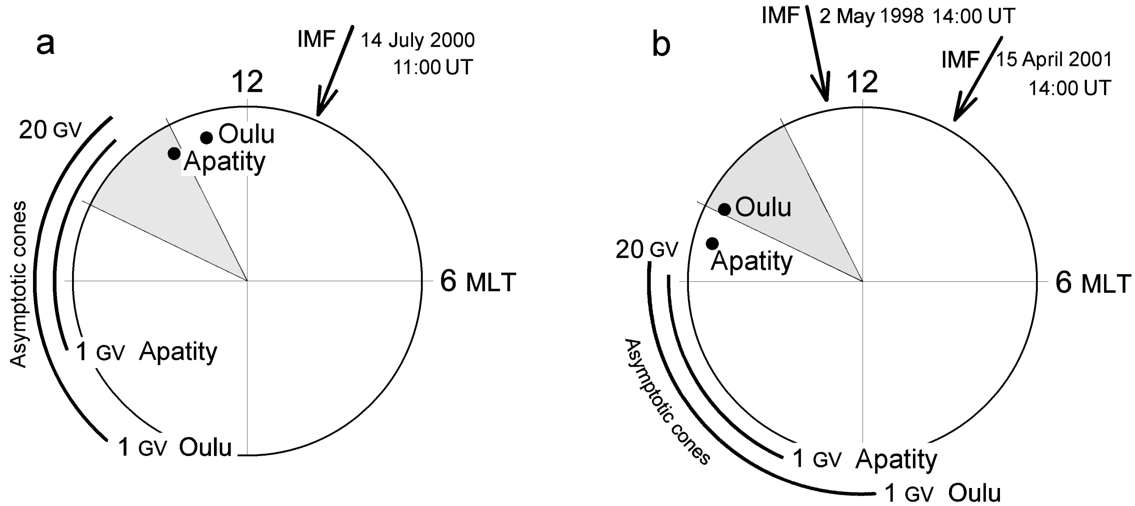

Fig.4. The schematic explanation of the effect Apatity-Oulu difference in GLEs. **a**: 14.07.2000, **b**: 2.05.1998 and 15.04.2001 events. The magnetic local time projections of the "14 MLT" sector, NMs Apatity and Oulu locations, their asymptotic cones as well as IMF field line direction are shown.

outside it (Fig. 4b). Accordingly, it seems that the magnetospheric modifications during the GLE event are most dramatic in the 14 MLT dayside sector, allowing an easier penetration of solar protons into the inner magnetosphere and to the ground. The probable mechanism for this special behaviour is the additional depression of the magnetospheric field caused by the magnetospheric current systems in this local time sector (Ostapenko and Maltsev, 2001).

When analysing the magnetospheric response to different solar wind parameters by a large number of satellite measurements a suppression of up to 20 % of the geomagnetic field (at the distance of 3-10 R_E) was found in the afternoon sector during periods with negative IMF B_Z component (Ostapenko and Maltsev, 2001). The physical reason for this magnetic anomaly in the 14 MLT sector are probably the enhanced inner magnetospheric currents induced by the enhanced convection due to a strong IMF negative B_Z component. In the three special GLE events where a large difference between Oulu and Apatity was observed the IMF had a strong negative B_Z component. This fact supports our suggestion that the easier penetration of solar protons in the 14 MLT sector is due to weakening of the magnetospheric field in this sector. Finally, we note that the 14 MLT sector (14-16 MLT) shown in Fig. 4 is only a statistical average and a similar difference may be found sometimes even slightly outside this region although all the three presently known cases do fall within this range.

6 Summary

We have studied the unusual difference in the increase profiles during three GLEs (14 July 2000, 2 May 1998 and 15 April 2001) between the two closely located neutron monitors of Apatity and Oulu. We noted that all these three special GLEs cases occurred at a time when the Apatity-Oulu pair was in the early afternoon MLT sector. Moreover, in all these cases the station with a higher count rate (Apatity on 14 July 2000, Oulu on 2 May 1998 and 15 April 2001) was located in the 14 MLT region where the maximum dayside auroral intensity and some other anomalous geophysical phenomena are located. We suggested that due to the additional depletion of the magnetic field in this afternoon MLT sector during disturbed conditions, it is easier for solar protons to penetrate into the inner magnetosphere than expected from commonly used magnetospheric models using statistical averages of the magnetic field.

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