MUON DETECTORS – THE REAL-TIME, GROUND BASED FORECAST OF GEOMAGNETIC STORMS IN EUROPE

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ABSTRACT

The present muon detector network in Japan, Australia and Brazil is described. This network represents an important tool for forecasting geomagnetic storms several hours in advance, because approaching CMEs and interplanetary shock waves are detectable with ground based cosmic ray telescopes through cosmic ray anisotropies. The present network, however, has a big gap in directional coverage over the northern Atlantic and European regions. Therefore the Alcatel Space / LPCE consortium recommended to ESA the inclusion of a muon telescope within the European Space Weather Programme.

1. INTRODUCTION

CMEs and shock waves propagate from the Sun into interplanetary space and are observable in near real time in the UV with coronagraphs on the ESA/NASA SOHO spacecraft. For instance the LASCO coronagaph images the propagation of CMEs up to 30 solar radii [1]. No data on the interplanetary propagation of CMEs and shock waves observed by SOHO are available beyond this distance except when the disturbances pass spacecraft orbiting inside 1 AU like those at the Earth-Sun L1 Lagrangian point. Therefore predictions of arrival at Earth largely depend on simulations of interplanetary propagation with, for instance, SOHO data as initial conditions. However industry and other space weather users need accurate forecasts of arrival times at Earth. This is only possible if the CMEs and shock waves are observed as early as possible during interplanetary propagation after they are outside the SOHO/LASCO viewing field.

Ground-level cosmic ray detectors scan various directions in space (including to the Sun) as Earth rotates. Daily variations in counting rates of ground based cosmic ray detectors reflect the anisotropic intensity distribution of galactic cosmic rays in space. These variations observed in local time have diurnal (a pure sine wave with a period of 24 hours) and semidiurnal components. The semidiurnal variation is well understood and results from interactions in the heliosphere of the outward moving solar wind and inward diffusing galactic cosmic rays, i.e. due to pitch angle scattering and adiabatic deceleration within the spatially varying interplanetary magnetic field (IMF). Semidiurnal variations have been observed by neutron monitors, ion chambers and muon telescopes from both hemispheres at Earth [2].

Earth directed CMEs and shock waves are detectable with ground-level cosmic ray muon telescopes earlier than with neutron monitors. In general the detectors observe a reduced flux of particles moving away from the shock, with small pitch angles, due to a cosmic-ray-depleted region behind the shock. This depletion is measured by the cosmic ray telescopes as intensity deficits of cosmic rays (of the order of 1% to 2%) at the ground. The first detection of the shock depends on the distance *r* as it is given in Eq. 1

$$r \sim 0.1\ \lambda_{\parallel} \cos \psi \tag{1}$$

where $\lambda_{\parallel}$ is the scattering mean free path cosmic ray particles of 10 GeV along the mean IMF and ψ is the angle between the Sun – Earth line and the mean IMF at the Earth [3]. For cosmic ray particles of 10 GeV (typical of particles recorded by neutron monitors) $\lambda_{\parallel}$ is of the order of about 1 AU. Therefore, an anisotropy arising from an interplanetary shock wave will be recorded by neutron monitors up to 5 hours before the shock wave arrives at Earth. However precursors of geomagnetic storms should be observed by muon telescopes much earlier (~24 hours) than by neutron monitors because muon detectors respond to higher energy cosmic rays (greater than 50 GeV) for which $\lambda_{\parallel}$ is much longer [4].

Between 1992 and 2001 the muon telescope network (Japan, Australia, Brazil) observed 17 geomagnetic storms with identifiable cosmic ray muon precursors, with typical first detection times ranging from 3 to 12 hours before onset of storm sudden commencement ([4], [5]). However many more geomagnetic storm precursors and much more precise determination of the propagation to Earth, and thus the storm arrival time, will be achieved if the gap in directional coverage over the northern Atlantic and European region is closed. Therefore the ALCATEL Space / LPCE consortium of the ESA Space Weather programme study recommended ground based instrument developments with high priority for a European muon telescope [6].

2. MUON DETECTORS ON GROUND

At present, cosmic ray precursors to geomagnetic storms are recorded by a network of ground-level muon telescopes ([4], [5]). Scintillator telescopes are located at Nagoya (Nagoya NST, Japan), Hobart (HST, Australia) and São Martinho (SMST, Brazil) whilst proportional counter telescopes are located in Antarctica (Australian Antarctic Station Mawson, Mawson-PC). The total number of all directional telescopes is 39.

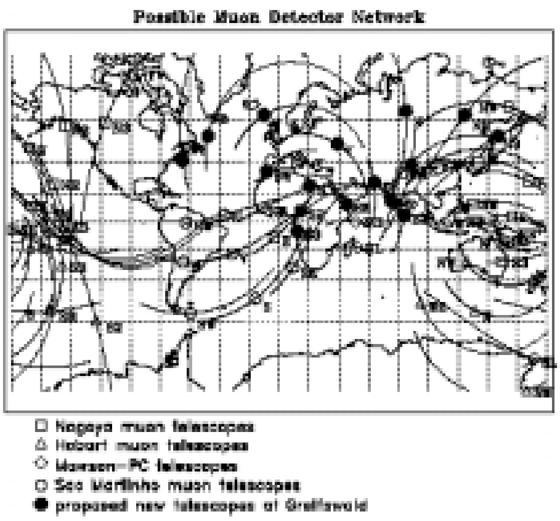

Fig. 1 Asymptotic viewing directions of the muon telescopes NST, HST, SMST, Mawson-PC and possible new telescope GST after correction for geomagnetic bending. The traces through the symbols (squares for Nagoya, triangles for Hobart, open circles for São Martinho, diamonds for Mawson-PC and filled circles for Greifswald) display the spread of the viewing directions corresponding to the central 80% of each telescope's energy response, related to a particle incident at each telescope measured at the median primary rigidity P_m (P_m for GST/Germany is given in Table 1, for the other telescopes see [4] and [5]).

The median rigidity P_m of primary cosmic rays recorded ranges from 53 to 119 GV. The hourly count rate is between 4.7 x 10^4 and 246 x 10^4 hr^{-1} with the statistical error for the hourly count rate between 0.06% and 0.46%. The symbols in Figure 1 display the asymptotic viewing directions (after correction for geomagnetic bending) of a cosmic ray muon incident at each directional telescope with median rigidity P_m including a possible new telescope at Greifswald in northern Germany (GST). The track through each symbol represents the spread of viewing directions corresponding to the central 80% of each telescope's energy response.

Table 1 shows the instrumental parameters for the proposed new Greifswald telescope system. The system would comprise two layers each with thirty-six 1 m^2 scintillators (6x6) operated in coincidence between appropriate pairs to generate the local viewing directions given in Table 1. The high hourly count rate equates to errors that range between 0.06% for vertical (V) and 0.26% for the most easterly view (E3), comparable with the other instruments in the global network.

Tab.1 Greifswald muon telescope asymptotic viewing direction, hourly count rate and median rigidity.

Local viewing direction	Count rate (hr^{-1})	Median rigidity (GV)	Asym. Lat. (°)	Asym. Lon. (°)
V	2577718	57.33	32.79	51.98
N	1182664	61.49	50.20	79.92
S	1182690	61.53	8.28	38.68
E	1176049	61.30	13.34	78.20
W	1185480	61.69	45.17	15.05
NE	577119	65.42	26.71	95.00
NW	580062	65.78	69.48	37.04
SE	576419	65.48	-2.39	64.21
SW	579831	65.74	18.04	11.86
N2	591681	79.99	58.23	106.89
S2	591146	79.99	-8.90	32.92
E2	589315	80.04	3.41	90.82
W2	592255	80.07	43.65	-16.21
N3	147937	103.91	58.00	133.70
S3	147910	103.91	-23.29	30.36
E3	147697	103.95	-4.34	101.13
W3	147978	103.88	36.58	-37.20

3. DETECTED PRECURSORS

Figure 2 shows observations for the period covering the onset of a geomagnetic storm (storm sudden commencement SSC) on September 9, 1992. The anisotropy as measured by the muon telescopes appears as the third plot from the top. The open and solid circles represent an excess and a deficit of cosmic ray intensity relative to the average and the diameter of each circle is proportional to the magnitude of deficit or excess (see 1% scale to the right of the plot). About 10 hours before the SSC an intensity excess in the sunward IMF direction became clearly evident. McMurdo neutron monitor observations show the long lasting nature of the event (second plot from the top). An enhanced muon intensity about 25 hours before the storm may also be present but, due to poor network coverage from –23 hours to –10 hours, the statistical significance is not sufficient to be certain.

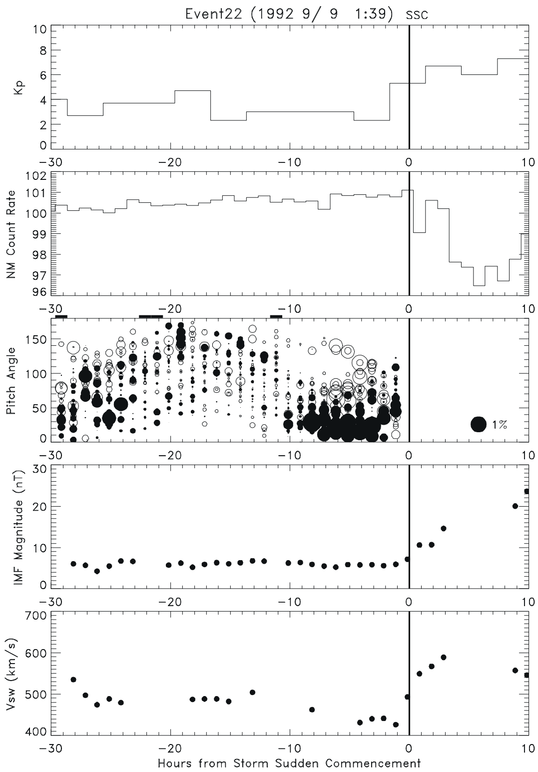

Fig. 2 Observations for the period covering the geomagnetic storm on September 9, 1992 (from top to bottom): K_p geomagnetic index, McMurdo neutron monitor relative count rate, anisotropy derived from the muon telescopes, IMF magnitude and solar wind velocity (for details see [4]).

Histograms of the distribution of the detected cosmic ray muon anisotropies as a function of the geomagnetic index Kp and the appearance time of precursors are shown in Figure 3 [4]. A total of 39 geomagnetic storms were analyzed, 17 of them are neglected due to poor network coverage. Of the remaining 22 storms, 7 had no precursor signatures (NP). Ten storm precursors are so-called loss cone types (LC, with intensity deficits confined in a small pitch angle region around sunward IMF direction) and 5 precursors belong to enhanced variance type (EV, increase or decrease of muon intensity independent of IMF direction). Two additional precursors of EV type were detected in 2001 [5].

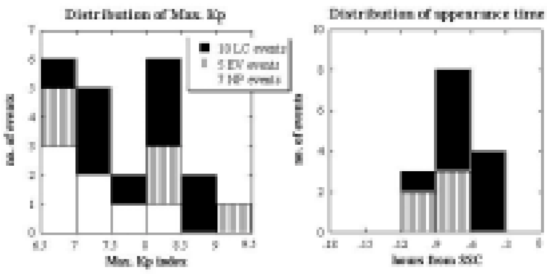

Fig. 3 Histograms of the maximum of K_p index (left) and the appearance time of precursors of geomagnetic storms (right). The selection criterion for the appearance time is a conservative estimation and the precursors may have been observed earlier in many cases.

4. CONCLUSION

The current muon telescope network allows early determination of the interplanetary propagation of space weather storms. However, only a full-time, all-sky coverage by means of an international cosmic ray muon detector network will allow reliable space weather forecasting to be developed. The method described could then be employed as a space weather forecasting service, allowing near real time predictions necessary for power and pipeline companies (because of CME and shock wave generated induced currents) as well as for satellite operators (because of high energy particle arrival).

5. REFERENCES

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