PROCEEDINGS OF SCIENCE

High latitude muon and neutron observation of the Forbush decrease during the May 2024 solar storm

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A series of intense solar flares occurred in May 2024. Among other effects, a remarkable Forbush decrease in the cosmic ray flux was observed on the Earth. This event was recorded by muon and neutron monitoring systems located at Svalbard, a high-latitude site with minimal geomagnetic shielding. For this analysis we employed three scintillator-based muon telescopes of the Extreme Energy Events (EEE) project, 14 channels of a Bonner Sphere neutron Spectrometer (BSS), and thermal and epithermal neutron sensors used for hydrological monitoring, all installed at the international research site of Ny-Ålesund, 78.9ºN in the Svalbard archipelago. Most sensors showed significant responses and correlation during the event. The maximal magnitude of the Forbush decrease was estimated to be ≈ 10-20% for thermal neutrons, ≈ 8-15% for high-energy neutrons, and ≈ 5% for muons. A correlation analysis of the time series provided by all these detectors during May 2024 was also performed, and is described in this contribution.

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1. Introduction

The EEE Collaboration has been promoting science in schools for more than 20 years through the involvement of students and teachers in fundamental physics research. One of the most complex and successful projects has been the construction and installation of 50 telescopes in high schools in Italy. EEE's telescopes [9] are based on the Multigap Resistive Plate Chambers (MRPC) technology and are built at CERN, where students, by contributing to their construction, have the opportunity to gain valuable experience in a prestigious research institute. The students are then also involved in the maintenance, management and analysis of the data.

In 2018 the collaboration built another series of telescopes, based on scintillators and read from Silicon Photo-Multipliers (SiPM), intended for measuring muon rates, but lighter and more compact to allow them to be installed in remote locations.

The first measurement campaign was carried out on board a sailboat, in the Arctic seas, during the summer of 2018 [1]. Later, measurements were carried out at different latitudes by transporting one of the detectors by car from southern Italy to northern Germany [2]. Finally, in summer 2019, three scintillator detectors, called POLA-R, were permanently installed at the International Research Base on Svalbard Islands, and their measurements are the subject of this paper.

In the same site, the Helmholtz Centre for Environmental Research (UFZ, Leipzig, Germany) is operating a Bonner Sphere Spectrometer for neutron detection [7] and a Cosmic Rays Neutron Sensor (CRNS) [8].

On initial analysis, the data from these three classes of detectors appeared difficult to compare. But an extraordinary geomagnetic storm in May 2024 offered a perfect opportunity to observe the response of the different instruments and compare their performance. On May 8, 2024, in the period leading towards the maximum of solar cycle 25, a series of coronal mass ejections (CMEs) and electromagnetic radiation (solar flares) were observed from an active region of the sun, called AR13664 [5] and [6]. A couple of days later, a noticeable decrease in the rate of cosmic rays was observed on the Earth's surface. This phenomenon, called *Forbush decrease* after the scientist who first observed it in 1938 [3, 4], was also measured by the above instruments at Svalbard, allowing us a comparative analysis of the different responses.

2. Installation site and detectors description

The Ny-Ålesund research station, which was formerly a mining village in King's Bay, offers infrastructure and services to research organisations interested in carrying out scientific research in the polar environment, and coordinates and facilitates contacts and collaborations between different countries and research groups.

The three scintillation detectors (POLA-1, POLA-3 and POLA-4[1]), are installed in facilities managed by the italian Consiglio Nazionale delle Ricerche (CNR); the Bonner Sphere Spectrometer is installed in the German-French station, while the Cosmic Ray Neutron Sensing device is located at 1 km distance, in an area devoted to permafrost studies (Figure 1).

[1] A fourth detector, POLA-2, is installed in the INFN Laboratory in Bologna as a reference

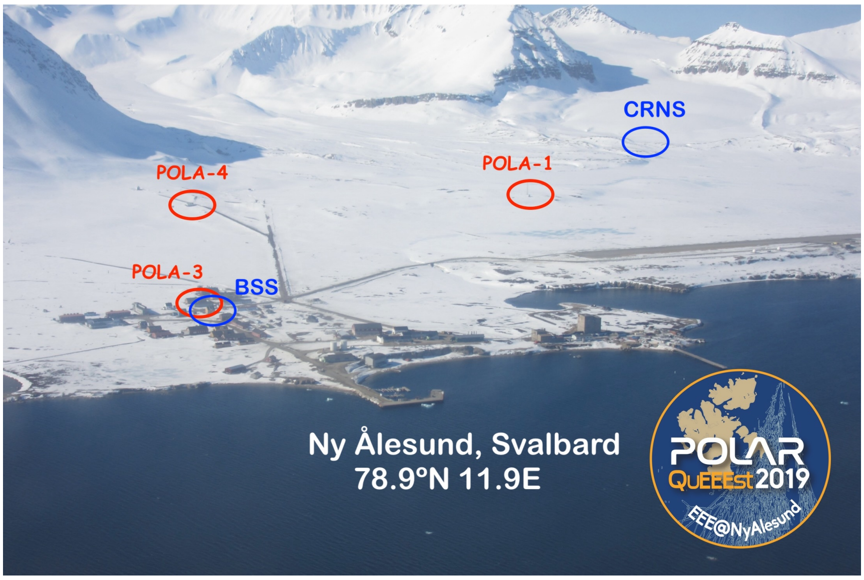

Figure 1: Aerial photo of Ny-Ålesund, with the locations of the instruments.

Figure 2: On the left, a close-up photo of one of the POLA-R muon detectors during assembly at CERN. On the right, the POLA-4 muon detector installed in the Gruvebadet Laboratory, at Ny-Ålesund

2.1 The muon detectors

The muon POLA-R detectors are compact, lightweight yet high-performance instruments, initially designed to be installed on a boat. Each one measures 78x56x30 cm^3 and weighs 50 kg. They consist of two planes of scintillators separated by 11 cm, each plane consisting of four tiles measuring 30x20 cm^2 each (Figure 2). A tile is read by two Silicon Photo-Multipliers (SiPMs). The power system, the readout electronics, and the trigger and data acquisition system are hosted in a box located at the bottom of the devices, together with several environmental sensors and a GPS timing system. A detailed description of the POLA-R detectors is given in [1].

This type of detector is able to detect particles from the secondary cosmic radiation, mostly GeV muons and energetic (10 MeV) electrons. It has a certain tracking capacity, given its segmentation, but is particularly efficient in measuring the rate of particles, secondary products of cosmic rays, on the earth's surface.

Figure 3: The Bonner Sphere Spectrometer (BSS) installed at Ny-Ålesund

Figure 4: The cosmic-ray neutron sensors (CRNS) installed at the Bayelva site, near Ny-Ålesund

2.2 The neutron counters

Subjects of this analysis work, together with the POLA-R muon detectors, are a Bonner Sphere Spectrometer (BSS) and a Cosmic Ray Neutron Sensor (CRNS).

The BSS has been installed in Ny-Ålesund for several years, and was recently put back into operation (Figure 3). It is made of 14 spheres, containing helium-3 thermal spherical neutron detectors. Each sphere is referred to by its diameter, ranging from 2 to 15 inches; 12 of these consist of hollow spheres made of high-density polyethylene (HDPE) of different thickness, which has the function of neutron moderator; one sphere is bare (to be mainly sensitive to thermal neutrons), and one is shielded with lead (to be sensitive to high energy neutrons, $> 10 MeV$).

At Bayelva, a site dedicated to the study of permafrost about 1 km far from Ny-Ålesund, a CRNS of type CRS1000 has been installed for a few years now (Figure 4). This CRNS consists of two helium-3 neutron detectors, one shielded with 2.5 cm of high density polyethylene and the other without shielding (bare). The shielded detector tube mainly measures neutrons in the epithermal region, while the bare detector mainly measures neutrons in the thermalised peak.

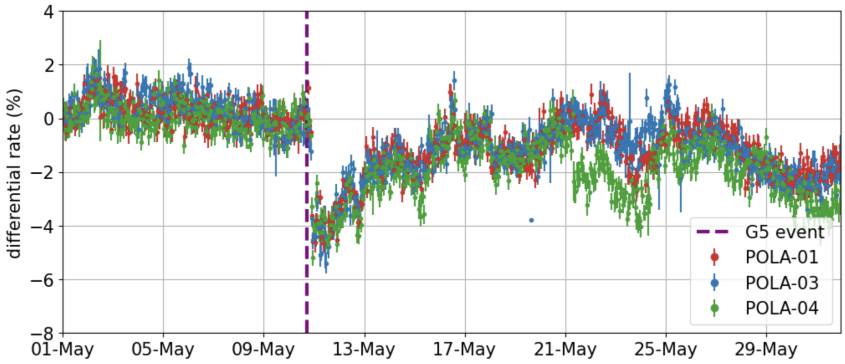

Figure 5: Differential rate of the POLA-1, POLA-3 and POLA-4 muon detectors, zoomed around the Forbush decrease period.

3. The geomagnetic storm of May 2024

Between May 8 and 13, 2024, an intense series of coronal mass ejections (CMEs) erupted from solar active region AR13664, culminating in multiple Earth-directed plasma blasts. These triggered a major geomagnetic storm between May 10–13—the strongest since March 1989—classified at G5 level.

The storm hit Earth on May 10, persisted through May 12–13, and involved multiple shock sheath phases that compressed the magnetosphere, caused widespread radio blackouts, GPS disruptions, satellite anomalies, visible auroras at unusually low latitudes, and elevated geomagnetically induced currents affecting power and pipeline systems.

On May 10, 2024, numerous particle detectors around the world recorded a Forbush decrease —a well-known phenomenon characterized by a sudden reduction in the flux of secondary cosmic ray particles at Earth's surface. This effect results from transient disturbances in the interplanetary magnetic field, acting as a more effective barrier against the propagation of galactic cosmic rays, leading to a temporary suppression of their intensity observed at ground level.

4. Particle rate measurements and the Forbush decrease of May 2024

The three muon detectors have been taking data since 2019 on a fairly regular basis. The events are recorded locally, are tagged with a GPS timestamp and are complemented by readings from environmental sensors. Periodically they are sent to the INFN CNAF computing centre in Bologna (Italy) for reconstruction and archiving. Here, the time series of the rate is prepared, by aggregating raw data into one-minute bins. The rates are subsequently corrected using the atmospheric pressure measured by the sensors. The barometric coefficient for this analysis was estimated over the 20 days preceding the Forbush event. No corrections other than the barometric one were applied, having verified that variations in environmental parameters such as temperature and humidity were not significant during the relatively short period considered in this study.

Figure 5 shows three curves representing the differential rate of the three POLA-R, in %. The differential rate is defined as $dI(t) = (I(t) - \langle I \rangle)/\langle I \rangle$, where $I(t)$ is the rate at time t, and $\langle I \rangle$ is the average rate, calculated in the period before the event.

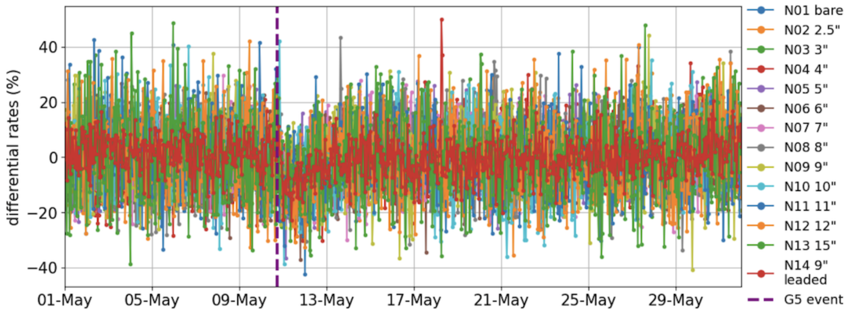

Figure 6: Differential rates (%) recorded by the 14 neutron sensors comprising the BSS.

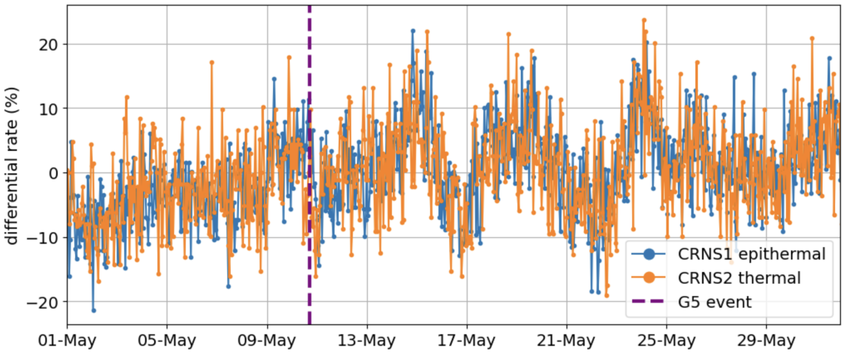

Figure 7: Differential rate of the two sensors, part of the CRNS.

The rates measured by the different channels of BSS and CRNS were also corrected for pressure, in order to obtain comparable measurements with POLA-R.

The differential rates for each of the 14 channels of the BSS are shown in Figure 6, while those obtained from the two sensors that make up the CRNS are in Figure 7. In all curves, the Forbush decrease can be recognised to a greater or lesser extent.

5. Forbush decrease magnitude

The large difference in spatial resolution makes a comparative study rather complex. For neutron detectors, which are characterised by very sparse sampling, the estimation of the amplitude of decay is prone to large systematic errors, which have been estimated by the experts of each instrument and are shown in Figure 8. In the case of muon detectors, on the other hand, the systematic errors are summed up in quadrature with the statistical errors derived from the aggregation into time bins.

The percentage amplitude values shown in Figure 8 represent the maximum decrement, defined as $dI_{FD}^{max} = (\langle I_{preFD}\rangle - I_{min})/\langle I_{preFD}\rangle$. For muon detectors, the maximum values go up to 5%, while for neutrons the maximum decrease can even approach 20%.

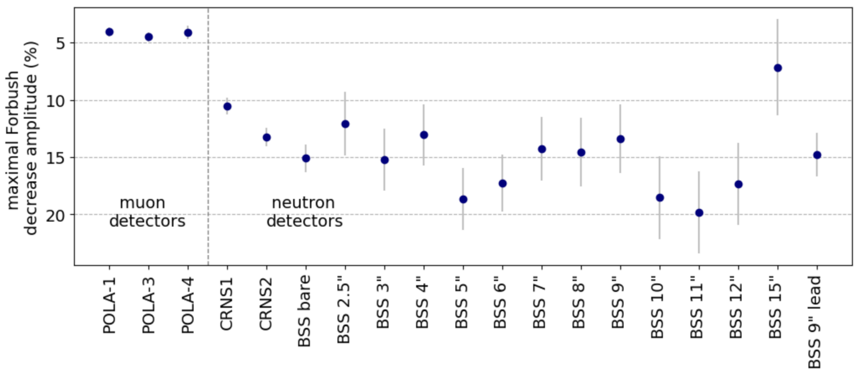

Figure 8: Amplitude of the differential rate decrease, calculated as the difference between the short-term pre-event average and the post-event minimum. The Forbush decrease is more visible for the neutron sensors.

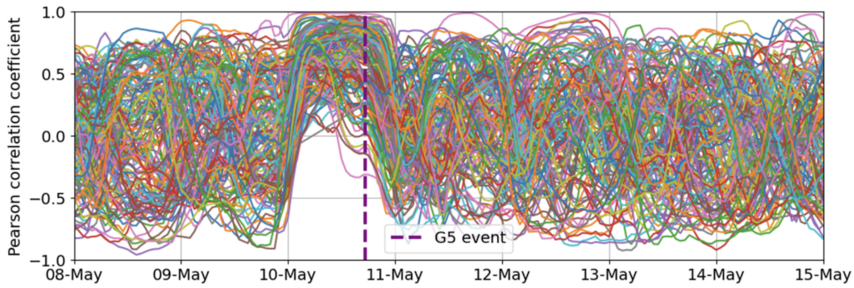

Figure 9: 181 curves of Pearson coefficients computed for all pairs of devices, evaluated for 1 day, assigned to the beginning of the interval

6. Correlation analysis

To compare the different instruments, we used Pearson's correlation coefficient, defined as $\rho_{X,Y} = cov(X,Y)/\sigma_X\sigma_Y$. This indicator, calculated hourly between the different pairs of time series truncated to the next 24 h, gives an estimate of the correlation trend over time. While before the event, the different sensors are rather unrelated, they all align in a concordant manner as soon as one enters the Forbush time window, only to resume the uncorrelated trend a few hours after the event.

7. Conclusions

The POLA, BSS and CRNS are very different instruments, developed completely independently by their respective institutes. However, they are installed in the same special place, a scientific station located in an area with a geomagnetic cutoff close to zero.

During the month of May 2024, a phenomenon occurred that affects all three, the Forbush decrease, consisting in the reduction of the secondary particle flux on the Earth's surface, as a result of the deformation of the interplanetary magnetic field due to the solar wind.

This event was particularly intense, and the comparison of the response of the three classes of detectors provided interesting insights into their characteristics. We estimated the amplitude of the decrease, observing that the neutron detectors are subject to a greater decrease, with respect to muon detectors.

We studied the evolution of the correlation between the individual detectors, calculating the running value of Pearson's coefficient, and found that a good agreement during the event did not persist during the recovery phase after the decrease.

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