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Investigation of the diurnal variation of cosmic rays at large latitudes by the detectors of the Extreme Energy Events Project

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Abstract The diurnal modulation in galactic cosmic ray flux observed on the Earth is a widely studied phenomenon. Most of the analyses of this effect have been undertaken with data obtained by neutron monitor stations distributed over the world. The effect may also be seen in muon detectors, although muons are affected in a different way than neutrons. Particularly interesting is a comparison between the data obtained from neutron stations and muon telescopes located in the same region. In this paper we report an investigation of the diurnal modulation of cosmic rays at large latitudes, based on the data collected by three scintillator telescopes of the EEE (Extreme Energy Events) Project, installed at Ny-Ålesund, in the Svalbard archipelago, at 79° N, during the period 2019–2025. Amplitudes and phases of the observed diurnal maximum in the cosmic ray flux were extracted in various periods by a harmonic fit of the averaged daily trend. Muon results were also compared to data collected in the period 2003–2025 by the Barentsburg Neutron Monitor Station, located not far from our detectors. The data, integrated along periods of one year, with a moving average in six months steps, show evidence of a diurnal modulation, with amplitudes of (0.05−0.1) %, smaller, roughly by a factor 2, than for neutrons, and a phase generally close to 12–16 h local time. No sensible differences were observed in the anisotropy parameters between solar nights and days in the polar region. The possible contribution of a second harmonic in the observed diurnal trend was also investigated.

1 Introduction

The flux of cosmic rays at the top of the Earth's atmosphere changes over time [1,2]. These changes may occur as a consequence of solar transient phenomena, such as the Forbush Decreases (FDs) and Ground Level Enhancements (GLEs). Periodically or quasi-periodically phenomena influence the cosmic ray flux. Long term variations also exist, which span periods of 11 or 22 years, related to solar cycles. Annual variations in the cosmic ray flux are also observed, as originating by an annual modulation of meteorological factors and solar activity. Short-term variations, with a period close to 27 days, have also been investigated, as they originate from the average rotation period of the Sun.

Diurnal variations may even occur along each day. These are believed to originate from the changing conditions of the Interplanetary Magnetic Field (IMF) and of the Earth's magnetosphere. These variations are explained as the result of combined effects of radial convection and inward diffusion along the IMF. While the radial convection would produce a higher cosmic ray flux when the solar wind flows toward the Earth, inward diffusion may lead to the dispersion of cosmic rays along all directions. A complex interplay between these aspects is at the base of a small anisotropy in the cosmic ray flux, peaking with a proper alignment of the solar magnetic field with the Earth's magnetosphere [3–5].

Diurnal modulation of cosmic rays may appear as a variation of the measured flux along the day with respect to its daily average value. Such modulation is often represented by an harmonic trend, with its amplitude (maximum excess with respect to the average) and phase (local time corresponding to the maximum). The amount of such excess is small, of the order of 0.1% for neutron detectors, and even smaller for muon telescopes.

Due to statistical fluctuations in the measured number of events, especially for small detectors, a clear modulation effect may only be seen in data collected over long periods, whereas data from individual days may be affected by large variations in the diurnal trend. A single harmonic fit is usually applied to the diurnal trend to extract the amplitude and phase of the modulation.

Although the diurnal modulation in the cosmic ray flux has been noticed since a long time, the parameters which describe the diurnal modulation, notably its amplitude and phase, have been investigated in a long series of more recent papers [6–12], exploiting the variation of these parameters over different epochs or in different solar cycles, the dependence on the latitude and altitude of the observation site, the sensitivity of the detectors to the different secondary components and the connection to the solar and geomagnetic activity.

Several studies have found that the anisotropy in the amplitude varies with the solar cycle, decreasing at solar minima and increasing at maxima [8,10,11], aligning with the 11-years solar pattern.

Also the phase (time of maximum) of the diurnal modulation has been observed to vary along the solar cycles, exhibiting a 22-years periodicity, being several hours earlier at the sunspot minima than at maxima. This has been discussed in terms of a negative radial gradient and possibly of a low solar wind speed [13].

Although these aspects have been known for nearly a century, they highlight the need for detailed studies of the diurnal variations even today. Measurements of the cosmic ray flux at high latitudes, although made difficult by the logistics of the observation sites, are of interest because of the small geomagnetic cutoff and may allow the study of peculiar aspects of cosmic ray physics.

The investigation of the diurnal variation in the cosmic ray flux has been frequently carried out with Neutron Monitor (NM) stations which are distributed over the world, including several which are located in polar regions. Muon detectors are generally installed at smaller latitudes, thus not permitting a direct comparison with the information obtained by NM.

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Since several years, the EEE Project [14], which manages a set of Multigap Resistive Plate Chambers (MRPC) muon telescopes installed in Italy and at CERN, has undertaken a series of activities even at large latitudes, by the use of scintillator-based small telescopes (POLA-R detectors). These have been used in various measurement campaigns at different latitudes.

In one of these campaigns, one detector was installed on board of a small vessel sailing to about 82° N, from Iceland to close to North Pole [15]. Additional activities with one of the POLA-R detectors have been organized to get precision measurements of the cosmic ray flux at different latitudes, by a campaign carried out on board of the Amerigo Vespucci Italian training ship [17] and by two further expeditions with a car travelling across Europe, from 35° N (South Sicily) to about 70° N (Tromsø, Norway), covering the overall latitude range 35° N - 82° N [16].

Since 2019, three of these detectors are permanently installed at Ny-Ålesund, in the Svalbard archipelago, at 79° N, and are providing a nice opportunity to carry out cosmic ray physics investigations even at latitudes close to North Pole, profiting of the availability of additional neutron detectors in the same area. Very recently a joint neutron-muon investigation of the Forbush decrease following the May 2024 solar storms has been carried out by the use of these detectors [18], and a study of the seasonal variations in the polar regions is currently in progress [19].

In this paper, we report the results of an investigation of the diurnal modulation of galactic cosmic rays which makes use of the dataset collected over the period 2019–2025 in the observation site of Ny-Ålesund by the POLA-R detectors. Amplitude and phase of the observed modulation have been extracted as a function of time. Results were compared with those extracted by the analysis of data made available by the Barentsburg Neutron Monitor [21], located not far from our observation site.

Section 2 briefly describes the experimental setup and the data selection and correction. Section 3 reports the analysis procedure and the results of the analysis.

2 Experimental setup

2.1 The observation site

The Svalbard archipelago is located in the Arctic, from 74° to 81° N. The largest island is Spitsbergen, on the northwest coast where the permanent research site of Ny-Ålesund at 78° 55' 30" N 11° 55' 20" E is located. The research infrastructure is owned and operated by Kings Bay, a Norwegian government enterprise, which provides permanent research facilities to many scientific institutions from different countries. Among these, the Dirigibile-Italia Station, managed by the Italian Council for Research (CNR), the Amundsen-Nobile Climate Change Tower and the Gruvebadet Laboratory are the buildings where the three POLA-R telescopes used for this analysis have been installed for long-term measurement campaigns.

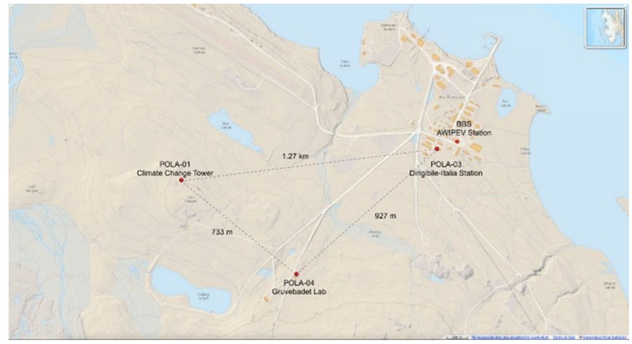

Fig. 1 Map of the Ny-Ålesund site on Svalbard. Marked in the figure are the locations of the three POLA-R detectors

The location of the three stations where the muon detectors (POLA-01, POLA-03 and POLA-04) are installed is shown in Fig. 1. The relative distances between the three detectors are shown in the picture and are about 730 m, 930 m and 1270 m.

2.2 The POLA-R detectors

The EEE Project [14] operates since 2007 a large set of cosmic ray telescopes based on Multigap Resistive Plate Chambers (MRPC). After their construction at CERN, most of them have been installed in Italian high school buildings and operated by school teams with students and teachers.

In 2018, the MRPC telescopes of the EEE Project were complemented by a set of small scintillator-based detectors (POLA-R) which have been then used in various measurement campaigns across Europe, in the Arctic and in the Mediterranean. Three of them are installed since 2019 at Ny-Ålesund. These detectors were already described in previous papers [15–19], hence only a brief recall of their main characteristics will be given here (Fig. 2).

Each POLA-R detector is made of two planes of plastic scintillators, with 4 tiles of (30×20) cm^2, separated by a vertical distance of 11 cm. The overall sensitive area of each detection plane is (40×60) cm^2.

Because of the rectangular shape of the detectors, the Field-Of-View (FOV) is a truncated pyramid, with maximum angles with respect to the vertical of 74° and 79° along the short and long sides respectively. However, as it may be verified by simple geometrical Monte Carlo simulations, the FOV is not uniform and particles at large angles are less likely to be detected, with an angular response which strongly favours particles arriving from close to the vertical.

Fig. 2 One of the POLA-R detectors. Two planes of plastic scintillators, with four tiles each (30 x 20) cm^2, are separated by a distance of 11 cm, and operated in coincidence as a telescope

The detector is enclosed, together with its electronics, in a light-tight box. The scintillation light produced in each tile by the passage of ionizing particles is read out by a pair of Silicon Photomultipliers (SiPM). The trigger for the data acquisition is provided by a coincidence between the top and bottom planes, with at least three signals from different SiPMs (majority logic). Various environmental sensors (of temperature, pressure, etc.) and a GPS-based synchronization system complement each detector.

Apart from breaks or malfunctioning, which required on-site interventions, the three detectors installed at Ny-Ålesund have been running since 2019, accumulating now more than six years of event-by-event collected data, resulting in about 15 billion recorded events. Several data analyses have been undertaken with this facility, to investigate the response to large solar events [18] and the annual and solar modulation in the cosmic ray flux [19].

2.3 Preliminary corrections and data selection

All data were previously corrected for the effect of the atmospheric pressure variations, as described in other recent analyses of data collected by these detectors [15–19]. The barometric coefficients were evaluated by a linear regression between the quantities (R - R_{avg}) and $\log(\Delta P/P_{avg})$, where P, R are the atmospheric pressure and the rate, P_{avg} and R_{avg} their average values and ΔP = P - P_{avg}. Their values were determined independently for each detector over the whole analysis period, and turned out to be −0.234%/hPa, −0.213%/hPa and −0.235%/hPa for POLA-01, POLA-03 and POLA-04 respectively.

The absolute detection efficiency of the POLA-R detectors had been previously measured against an external detector able to track particles from the secondary cosmic radiation, mostly GeV muons and energetic (>10 MeV) electrons, and found to be around 96%. The response of SiPM to the local temperature is controlled by an online temperature-dependent bias regulator.

Continuous monitoring of individual SiPM efficiencies over time was achieved by a comparison between the number of events with three and four SiPMs firing, similar to other investigations carried out with the same detectors [15–19], allowing a pseudo-efficiency correction to the dataset.

Atmospheric temperature seasonal variations are an important aspect when measuring the cosmic ray flux over long periods. The investigation of this aspect for the data collected in the six-years period 2019–2025 by our POLA-R detectors has been described in detail elsewhere [20]. In that paper, we used atmospheric temperature data collected by radiosonde monitoring over the same geographical region, providing temperature profiles up to an altitude of 35 km, with various atmospheric correction models. In the present case however, since we are using individual daily averages of the cosmic ray flux, we only compare values of the flux along the 24 h to their daily average, which is less affected to a first approximation, from long-term, seasonal variations linked to the overall atmospheric temperature profile.

Corrected daily averages of the count rates were evaluated for each of the three detectors over the entire period of data taking considered in this analysis, from June,4th, 2019 to December 18th, 2025 (2389 days), starting from 1-hour integrated cosmic ray rates. Apart from a long period, in 2020–2021, when one of the detectors (POLA-01) was not operational, hence not giving results for this analysis, short

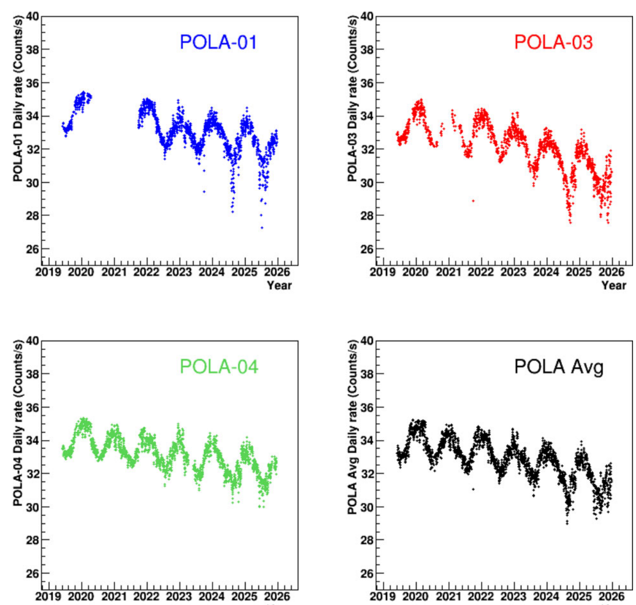

Fig. 3 Daily average rates of the three POLA-R detectors over the entire period of data taking, starting from June 4, 2019. The bottom right plot shows the average of the day-by-day available detectors. Only days with a complete 24-hours coverage have been considered

breaks or malfunctioning resulted in a number of days missing or with a non-complete 24-hours coverage. A selection was done considering only days with no missing data, i.e. where the daily average could be properly evaluated by the presence of all 24-hours bins. Although this selection slightly reduces the amount of available data (by about 15 %), it results in a more reliable dataset, which is important especially in view of this analysis. In view of the extraction of results on the observed diurnal anisotropy, we verified that the missing data were generally randomly distributed over the six-years period. Moreover, we also checked that either recovering those days with a few hours missing in the data taking, or randomly removing additional days, up to 10% more, did not alter the results.

Figure 3 shows the daily rates of the three individual detectors, together with the daily averaged rate of the detectors operating each day (bottom right plot).

All time series show a clear modulation of the rate, with a period of approximately one year. Investigation of the (pseudo)-periodicity in these data has been discussed in a separate paper [19], making use of the Lomb-Scargle periodogram technique.

3 Analysis of diurnal modulation

3.1 Analysis procedure

To analyze the diurnal modulation in the measured cosmic ray flux, the dataset of each detector, which includes the GPS time stamping of individual events, was integrated in 1-hour bins, and compared to the corresponding daily average, obtaining 24 hourly values, which represent the excess (or deficit) percent difference with respect to the average.

Large fluctuations are observed in each individual day, due to the typical count rate of the detectors (about 30 events/s), so no definite excess or deficit, expected to be of the order of 0.1 %, may be seen. For such reason, the percent distributions of the differences with respect to the daily average need to be extracted for each of the 24 hourly bins, considering a large

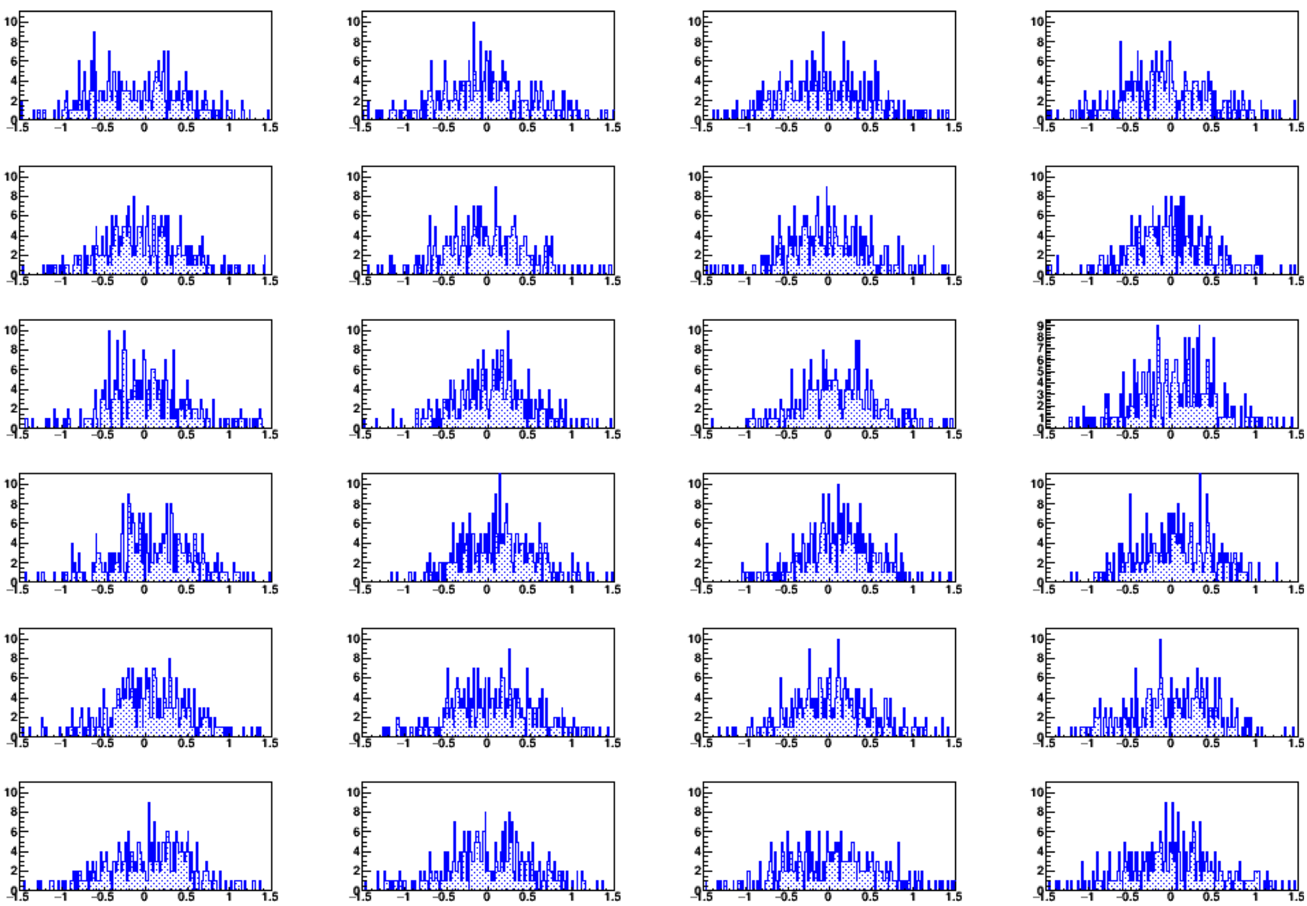

Fig. 4 Distribution of the daily differences with respect to the daily average, considered for each of the 24 1-hour bins. The data in this figure were collected with the POLA-01 detector in 2024. The 24 histograms refer, from top left to right bottom, to the 24 1-hour UTC time bins, 00–01 h, 01–02 h

number of days. In a preliminary analysis we considered a period of one year to test the procedure.

Figure 4 shows as an example the 24 distributions obtained for one of the detectors (POLA-01) during the entire 2024, where 356 days (out of 366) were selected by the requirement of complete available data during the 24 h. The 24 histograms refer (from top left to right bottom) to the UTC time bins (00–01 h, 01–02 h,...). Although large fluctuations are observed, with an RMS of the order of 0.5%, considering a large number of days allows to extract a reliable centroid of the distribution. To avoid outliers in the distributions, which may originate from individual days where some large variation in the cosmic ray flux may be present for a short time, for instance as due to technical problems in the detection setup, a cut at ± 1.5% was introduced. Only a negligible effect was in any case observed by the introduction of this cut.

The centroids of the various distributions, together with their standard deviations of the mean, were considered as an estimate of the hourly difference with respect to the daily average, integrated over the one-year period.

Figure 5 shows the diurnal variation (in percent) of the cosmic ray flux with respect to the daily average, obtained from the analysis of data collected by one detector (POLA-01) for the entire 2024 data taking period, obtained by the distributions shown in Fig. 4. The time is expressed in UTC time, whereas local time for POLA-R detectors, due to their longitude, is 0.8 h ahead. While the same analysis carried out on short periods (days/weeks) does not show a definite modulation, a clear trend can be observed integrating over a period of 1 year.

As it is seen, a maximum is observed around early afternoon, with an amplitude slightly smaller than 0.1%. The trend was fitted by a single harmonic function

$$F(t) = A + B\, cos\, (\omega(t - \varphi))$$

where A is the average value, $\omega = 2\pi/24$ and φ is in hours.

In this case the values of the amplitude and phase of the observed anisotropy, extracted from the fit, resulted to be B = (0.070 ± 0.007) % and φ = (13.6 ± 0.4) hours (UTC time), corresponding to 14.4 h local time.

Although the contribution of a second harmonic has been sometimes discussed [6,12], most of the analyses reported so far made use of a single harmonic to parametrize the diurnal trend. This is also the method we followed in the present analysis. However, at the end of this Section, we will discuss in more detail a possible contribution of the second harmonic in the diurnal trend integrated over large observation periods.

A temperature-dependent pseudo-efficiency correction has been applied to the data, as discussed in Sect. 2.3, similar to previous investigations with these detectors [15–19]. However, to check whether small residual effects of the local

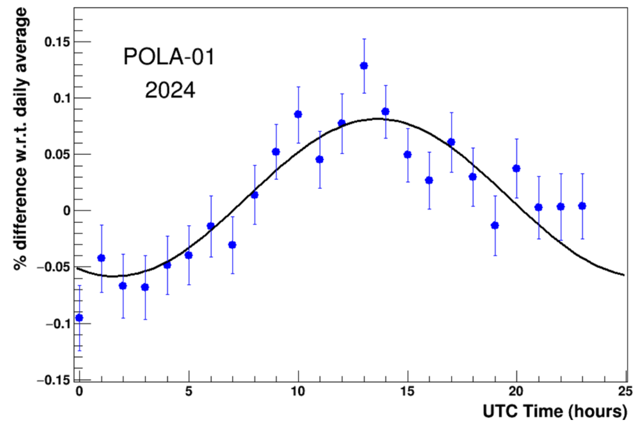

Fig. 5 Percent diurnal variation of the cosmic ray flux with respect to the daily average along the 24 h. The data in this figure were collected with the POLA-01 detector in 2024. Time is expressed in UTC time, whereas local time for the POLA-R detectors is about 0.8 h ahead because of their longitude

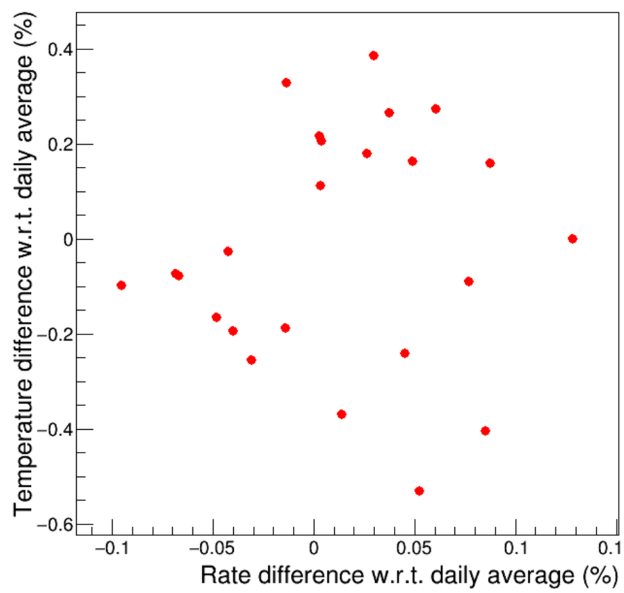

Fig. 6 Correlation between the differences of the hourly rate and of the temperature with respect to their daily averages. The data in this figure were collected with the POLA-01 detector in 2024

temperature of the detector electronics, which is measured by sensors placed close to it, could influence the results, the same analysis procedure was applied to the time series of the temperature values. Daily averages of the local temperature were evaluated along all the year and the hourly differences with respect to the average were considered, similar to the cosmic ray rates, over one year. Although variations of the local temperature, mostly within ± (0.2−0.3) % are observed, such variations were seen to be uncorrelated with the corresponding variations in the cosmic ray flux, as it is seen in Fig. 6.

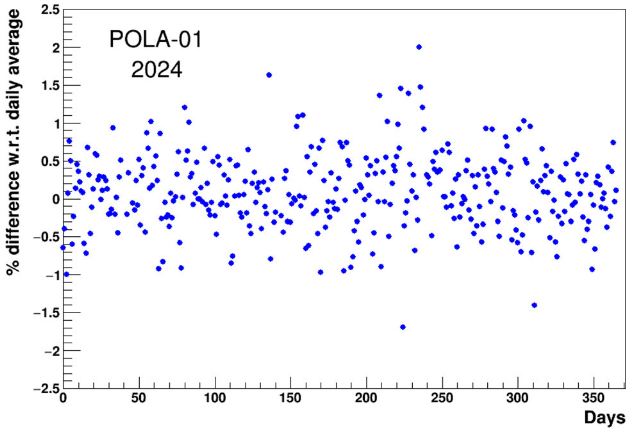

Fig. 7 Percent difference of the cosmic ray flux (considered in the UTC time bin 11:00–12:00) with respect to the daily average, measured by the POLA-01 detector, as a function of the time, along all the year 2024

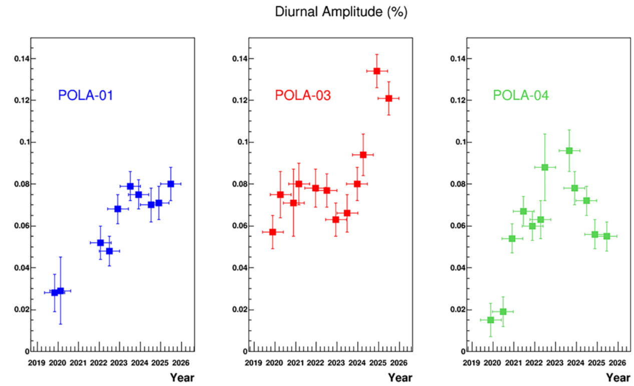

Fig. 8 Amplitude of the diurnal variations as a function of the time, for the period from 2019 to 2025, for the three POLA-R detectors. The effective time for each point in the plots was evaluated considering in each period of one year the days where complete data were available. A moving average was considered, with a time step of approximately six months between consecutive values. The horizontal bars denote the widths of the integration interval, ±0.5 years, while the uncertainties in the amplitudes were estimated by the harmonic fits

3.2 Results

Diurnal variations of the cosmic ray flux, as parameterized by the values of the amplitude and phase of the observed maximum, was investigated along the period June 2019-December 2025 for the three POLA-R detectors.

No large variations in the amplitude or phase were observed as a function of time in short periods, of the order of weeks/months. As an example, for one of the detectors (POLA-01), Fig. 7 shows the distribution of one of the 24% amplitude differences with respect to the daily average (the one corresponding to the UTC time bin T=11:00–12:00), as a function of time, along all the year 2024. The figure also shows that only in a few days along the year the variations slightly exceed the limits of ± 1.5% which were used as a cut.

Time windows of one year were considered for the analysis of data measured by the POLA-R detectors. To have information also in smaller time steps, a moving average (over a period of one year) was however considered, with a shift of six months. The effective time within each period of one year was estimated considering the days where complete data were available.

Figures 8 and 9 show the amplitude and the phase of the observed maxima for the individual detectors, along the 2019–2025 period. The horizontal bars denote the widths of the integration interval, ±0.5 years, while the uncertainties in the amplitude and in the phase were estimated through the harmonic fits.

The amplitude of the diurnal variation is generally smaller than 0.1% over the last years. Although with large fluctuations, larger values of the amplitude are observed in the second half of the 2019–2025 period.

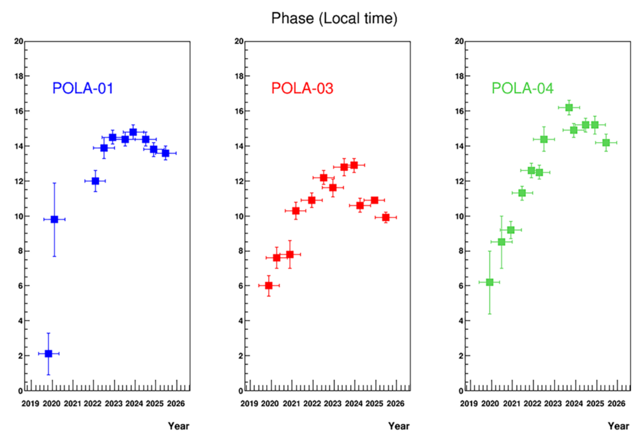

Fig. 9 As for Fig. 8, for the phase of the diurnal variations

Table 1 Diurnal anisotropy parameters extracted by the three POLA-R detectors over the entire 2019–2025 period

Detector	Amplitude (%)	Phase (Local time)
POLA-01	0.058 ± 0.003	13.9 ± 0.2
POLA-03	0.082 ± 0.004	10.6 ± 0.2
POLA-04	0.048 ± 0.003	13.6 ± 0.2

One of the detectors, POLA-03, shows some discrepancy with respect to the other two, which exhibit comparable values. Even the phase is peaked at an earlier time in POLA-03 than in POLA-01 and POLA-04. This may originate however by larger instrumental instabilities in this detector, as sometimes noticed in previous investigations.

This reflects even in some difference between the values of amplitude and phase for the three detectors over the entire 6-years period (Table 1).

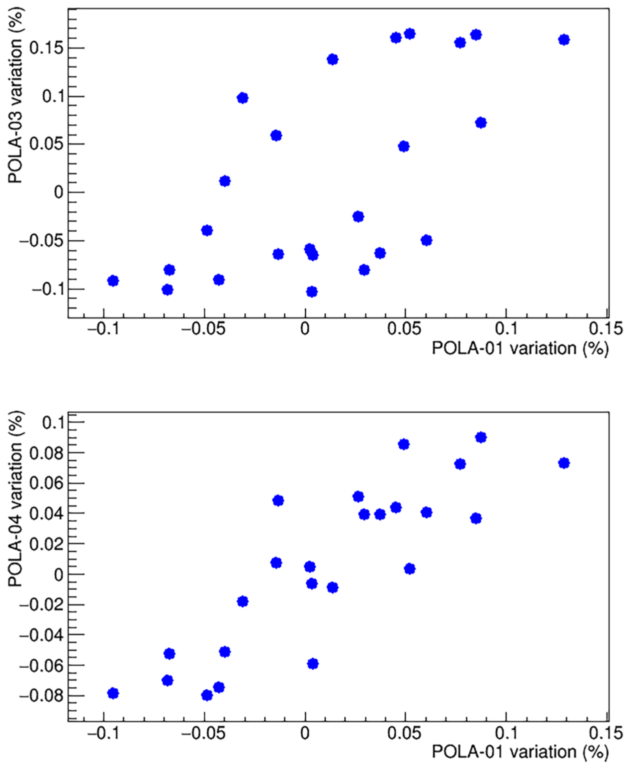

Fig. 10 Correlation plots of the hourly differences with respect to the daily average for the POLA-01/POLA-03 pair (top, Pearson coefficient = 0.63 ± 0.13) and POLA-01/POLA-04 pair (bottom, Pearson coefficient 0.85 ± 0.06)

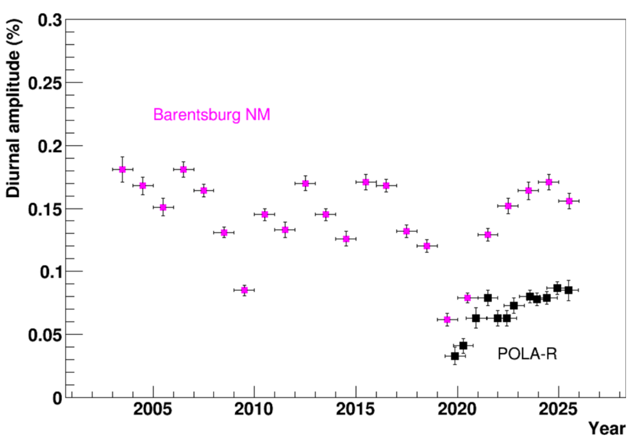

Fig. 11 Amplitude of the diurnal variation in the cosmic ray flux observed for the Barentsburg Neutron Monitor (pink symbols) and for the POLA-R detectors (average from three detectors, black symbols)

The phase expressed in local time (Fig. 9) also shows a clear increasing trend over this period. Values of the phase in the early afternoon may be observed in the last few years, while the phase is shifted to earlier times in the previous years. Similar findings, related to the sun activity, have been noticed even for the data extracted from Neutron Monitors [8,10,11].

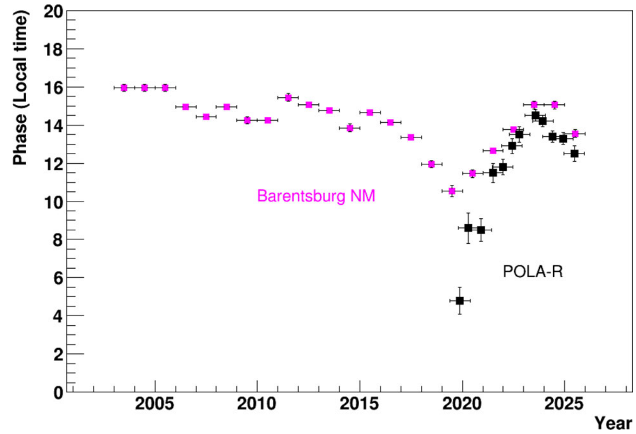

Fig. 12 Phase (Local Time) of the diurnal variation in the cosmic ray flux observed for the Barentsburg Neutron Monitor (pink symbols) and for the POLA-R detectors (average from three detectors, black symbols)

Apart from some difference between the three POLA-R detectors, the diurnal variations observed by all of them are correlated, as it may be observed in Fig. 10, which shows a correlation plot between the 24 hourly differences with respect to the average for the POLA-01/POLA-03 pair (top) and for the POLA-01/POLA-04 pair (bottom). Pearson correlation coefficients for the two plots are 0.63 ± 0.13 and 0.85 ± 0.06 respectively, which, for N = 24 points, denote a significant correlation at the level of 5% ($r_{0.05}$ = 0.37).

To compare our results with those obtained from a Neutron Monitor located at high latitude, in a geographical position close to our muon detectors, we analyzed the 1-hour time series of the cosmic ray rate available from the Barentsburg Neutron Monitor [21] over a longer period, from 2003 to 2025, spanning two solar cycles. The analysis was carried out with the same procedure as for our data, keeping the same criteria for data selection. Amplitude and phase of the diurnal variations observed by the three POLA-R detectors were combined into their average value for a comparison with the Barentsburg data. Figures 11 and 12 show the results.

Deeps around 2009 and 2019–2020 were observed along the years both in the amplitude and (to a lesser extent in 2009) in the phase. This is in general agreement with previous findings which state how the amplitude of the cosmic ray diurnal variations varies with a period of one solar activity cycle (11 years), while the phase varies with the period of one solar magnetic cycle (22 years) [8]. The amplitudes of the diurnal anisotropy exhibit their lowest values at solar minima, while the highest values are generally observed close to solar maxima. Investigations carried out over very long periods (44 years, four solar cycles) with data from multiple Neutron Monitor stations [8] have also allowed to observe differences between odd and even solar cycles.

The amplitudes extracted by the three POLA-R detectors, mainly sensitive to muons, are lower than the ampli-

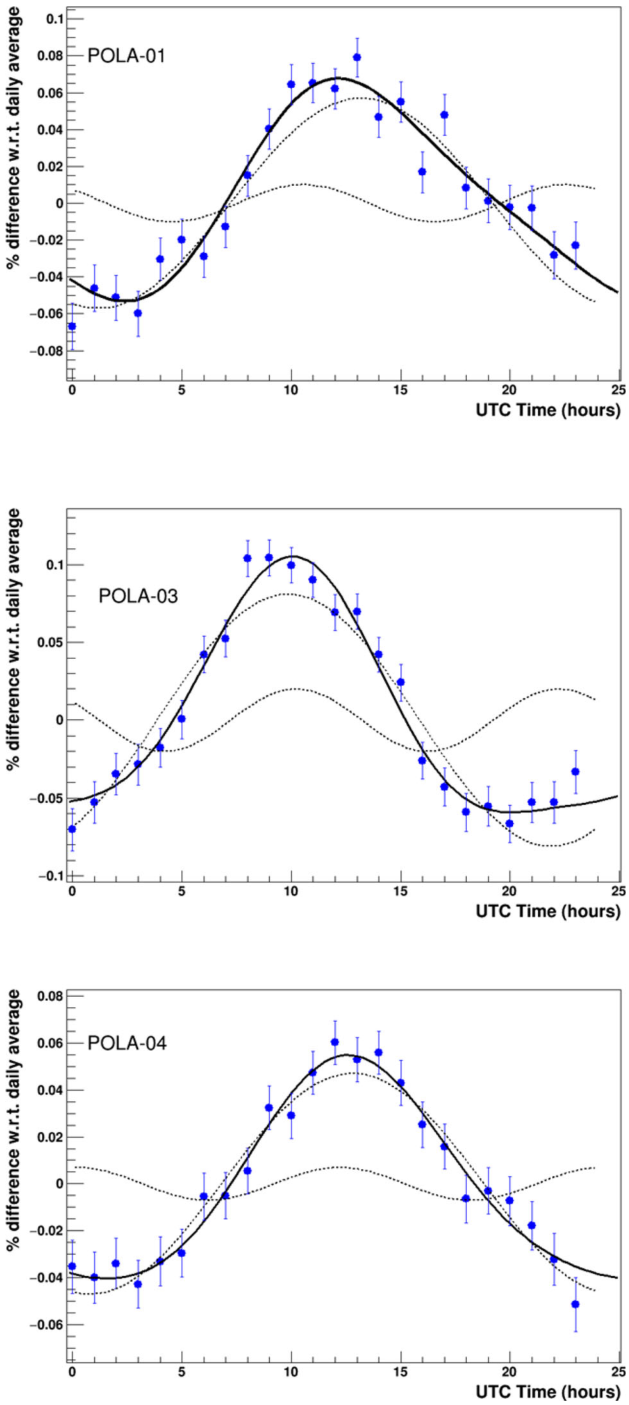

Fig. 13 Diurnal trends observed for the three POLA-R detectors over the complete period (2019–2025) considered in the present analysis. A fit with the contribution of the first and second harmonics is shown as a solid line. Dotted lines represent the individual contributions of the two harmonics

tudes observed by the Barentsburg NM, about a factor 2, but reflect the same trend over the last years, with a pronounced miminum around 2019–2020, similar to the data measured by the NM.

Table 2 Diurnal anisotropy parameters (amplitude in % and phase in local time, LT) for the three POLA-R detectors over the entire 2019–2025 period, extracted by a fit with the first two harmonics

Detector	Ampl.(%)/Phase (LT) 1st harmonic	Ampl.(%)/Phase (LT) 2nd harmonic
POLA-01	0.057/14.0	0.010/11.4
POLA-03	0.081/10.7	0.020/11.0
POLA-04	0.047/13.6	0.007/13.0

The phase of the diurnal variation shows a clear minimum around 2019–2020 for the Barentsburg data, shifting from the early afternoon to about 10 o'clock in the morning. Similar shifts to earlier hours have been observed over the last solar cycles in data from multiple NM stations [8]. This shift is more apparent for the muon detectors, where the phase goes down in 2019 as early as 5 o'clock in the morning, and even in 2021–2022 it is sensibly lower than the corresponding phase observed by the NM.

Although the differential analysis of the present data has been carried out by the use of a single harmonic, we investigated a possible contribution from a second harmonic, fitting the diurnal trend observed for each detector. To reduce statistical uncertainties, we considered the complete period 2019–2025, fitting by the function

$$F(t) = A + B_1 \, cos \, (\omega(t - \varphi_1)) + B_2 \, cos \, (2\omega(t - \varphi_2))$$

where A is the average value, B_1, B_2 represent the amplitudes of the first and second harmonic (24-hours and 12-hours periods), and φ_1, φ_2 the corresponding phases in hours.

Figure 13 shows the result of the fit carried out on the diurnal trend of the three POLA-R detectors over the complete dataset. Dotted lines show the individual contribution of the first and second harmonic, while the solid line is the sum of the two contributions. A better fit is clearly obtained by the inclusion of the second harmonic. The amplitudes of the second harmonic range between 15 % and 25 % with respect to the amplitudes of the first harmonic. However, the parameters describing amplitudes and phase, as extracted by the standard analysis with a single harmonic (Table 1), are not sensibly altered, as reported in Table 2.

It must be noted that the same analysis was performed by us on a large dataset of neutron data (2010–2024) from the Barentsburg NM, only showing a negligible contribution from the second harmonic, less than 4 % (Fig. 14).

The possible impact of a second harmonic in the diurnal trend of cosmic rays is certainly of interest and may deserve further studies in the future, with larger datasets (Table 2).

Compared to locations at smaller latitudes, polar regions are characterized by long time intervals (polar "nights" and "days") where the influence of the Sun may produce in principle a difference in the air ionization and magnetic field.

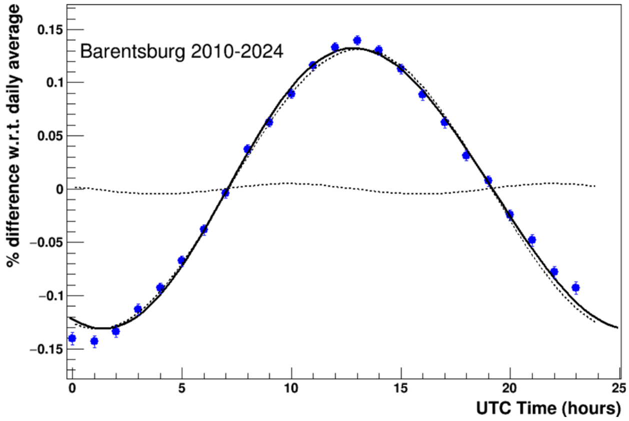

Fig. 14 Diurnal trend extracted by the Barentsburg NM in the period 2010–2024. A fit with the contribution of the first and second harmonics is shown as a solid line. Dotted lines represent the individual contributions of the two harmonics

The Earth's magnetic field exhibits distinct diurnal and seasonal variations in the polar regions due to differences in ionospheric electrical currents driven primarily by solar illumination. During polar day (local summer), the ionosphere is continuously sunlit, leading to high ionospheric conductance. During polar night (local winter), the lack of solar illumination results in a dark ionosphere with much lower conductance. The illuminated ionosphere during polar day allows for regular daily variations in the magnetic field, largely driven by the ionospheric wind dynamo and the interaction with the Interplanetary Magnetic Field. The magnetic field variations are more heavily influenced by magnetospheric processes and the specific components of the IMF, rather than the ionospheric dynamo, during polar nights. As a result, the Earth's magnetic field may experience differences during polar nights and days which may affect in turn the diurnal variations of cosmic rays.

To check for possible differences in the anisotropy parameters describing the diurnal variations, we considered the data from the Barentsburg Neutron Monitor in the period 2020–2024, splitting the data into polar nights periods (September 15–March 15) and polar days periods (March 15–September 15), extracting the average amplitude and phase during the two intervals. The average amplitude turned out to be (0.146 $\pm$ 0.005) % during the polar nights and (0.158 $\pm$ 0.005) % during the polar days, with UTC phases of 12.5 $\pm$ 0.15 (polar nights) and 13.2 $\pm$ 0.15 (polar days), i.e. comparable values within the uncertainties for the amplitude, and only a slight difference in the phase. The same analysis was carried out also for the data collected by the POLA-R detectors in the same period, considering the average from the three detectors, obtaining amplitudes of (0.062 $\pm$ 0.003) % during the polar nights and (0.072 $\pm$ 0.003) % during the polar days and UTC phases of (11.7 $\pm$ 0.2) hours (polar nights) and (11.4 $\pm$ 0.2) hours (polar days). Even in this case, no clear difference has been observed in the anisotropy parameters during polar nights and days.

Apart from the differences in the detailed processes leading to the production of neutrons and muons, and the different influence of the geomagnetic field, it has been noted that the geometrical properties of the neutron monitors and of the muon telescopes, especially for detectors located in polar regions, may also play a significant role. While NM have a larger geometrical acceptance, muon telescopes have an acceptance close to their geometrical viewing. Measurements carried out with specific Neutron Monitors having a narrow acceptance have shown diurnal modulations much smaller (0.03 %) than the usual NM, whose amplitudes range between 0.16 and 0.4 % [22].

Since even our muon telescopes have a Field-Of-View which favours incoming particles with direction close to the vertical, this may perhaps justify why the observed amplitudes of the anisotropy is small.

4 Concluding remarks

In the present investigation, an analysis of the diurnal modulation of the cosmic ray flux has been carried out employing a six-years dataset obtained by three muon telescopes installed in a high latitude site. The data, properly integrated along periods of one year, with a moving average, such as to obtain information in six-months steps, show evidence of a diurnal modulation, which over the last few years reached an amplitude of 0.07 % and a phase generally close to 12–16 h local time. These values however were sensibly smaller in the preceding years, with an amplitude going down to about 0.03 % in 2019–2020 and a phase shifting to the morning (6–8 h local time).

Muon data have been compared with neutron data obtained by the Barentsburg Neutron Monitor, located at a similar latitude as for our detectors, finding that the observed change of the amplitude and phase of the diurnal modulation follows a similar trend as for the neutron detector. The phase of the observed diurnal maximum in the muon flux, in particular, is close in recent years to that observed for neutrons, with a deeper minimum around 2019–2020. The observed amplitudes for muons were seen to be smaller, roughly by a factor 2, than for neutrons. No sensible differences were observed over the last few years in the anisotropy parameters between solar nights and days.

An attempt to check the presence of a second harmonic in the diurnal trend of cosmic rays detected in a polar region showed that this contribution is very small in neutron data, whereas a larger impact may be seen in the data collected by the muon telescopes. This aspect however may require further investigation with a larger dataset.

Measurements of the diurnal modulation carried out at polar latitudes with both neutron and muon detectors are not common. Some results obtained with Barentsburg and Apatity NM data were reported by Balabin et al. [23] who suggested that muon telescopes in the polar regions may be suitable to study the effect of cosmics originating from the north pole of the ecliptic.

These aspects point out the relevance of combined measurements of neutrons and muons in the same site, especially in polar regions, and it is hoped that additional data collected with the EEE muon telescopes at Ny-Ålesund in the next years could further contribute to the topic.

Another component of the anisotropy observed in the cosmic ray flux is associated to the solar Compton-Getting (C-G) effect, which is a relativistic kinematic effect of Earth's motion around the Sun. Recent measurements obtained by NM stations seem to point out that the anisotropy of the C-G effect may be as small as 0.04 %, with a phase around 6:00 Local Time, so generally smaller and located at a different phase with respect to the solar diurnal modulation arising from co-rotation of cosmic rays with the IMF. C-G anisotropy effects should be moreover independent of the solar activity. While small effects arising from C-G anisotropy cannot be completely ruled out, it is likely that only much more precise measurements, possibly sensitive to the particle energy, could disentangle between these effects.

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Data Availability Statement This manuscript has no associated data. [Authors' comment: Data sharing not applicable to this article as no datasets were generated or analysed during the current study].

Code Availability Statement This manuscript has no associated code/software. [Authors' comment: Code/Software sharing not applicable to this article as no code/software was generated or analysed during the current study].

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