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A.Ne.Mo.S — Athens Neutron Monitor Station (A.Ne.Mo.S)

NMDB — neutron monitor database

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Cosmic ray diurnal anisotropy during extreme events of the period 2001-2014

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Abstract: The diurnal variation of cosmic ray intensity, based on the records of two neutron monitor stations at Athens (Greece) and Oulu (Finland) for the time period 2001 to 2014, is studied. This period covers the maximum and the descending phase of the solar cycle 23, the minimum of the solar cycles 23/24 and the ascending phase of the solar cycle 24.These two stations differ in their geographic latitude and magnetic threshold rigidity. The amplitude and phase of the diurnal anisotropy vectors have been calculated on annual and monthly basis. From our analysis it is resulted that there is a different behaviour in the characteristics of the diurnal anisotropy during different phases of the solar cycle and during extreme events of cosmic ray activity, such as Ground Level Enhancements, Forbush decreases and magnetospheric events due to strong solar phenomena. These results may be useful to the Space Weather forecasting and especially to Biomagnetic studies.

1. Introduction

Cosmic rays are particles at very high energies from extraterrestrial sources within or outside the Milky Way. The cosmic radiation has high stability and isotropy in galactic scale. Nevertheless, the Sun and the interplanetary magnetic field result in anisotropies and variations in both the energy spectrum and the intensity of cosmic radiation as a function of space, time and energy. The diurnal anisotropy of cosmic ray intensity is an anisotropic, short-term variation of local time with a periodicity of 24 hours due to the rotation of the Earth around its axis and consequently the rotation of cone detectors of cosmic radiation (Fig. 1), *(Pomerantz and Duggal, 1971; Ahluwalia, 1988)*. Diurnal variation is mainly due to local anisotropy of galactic cosmic ray flux due to the convection by the solar wind and the diffusion along the interplanetary magnetic field (convective-diffusive theory), *(Sabbah, 2013)*.

In this work the diurnal anisotropy during extreme cosmic ray events recorded at the Athens and Oulu neutron monitor stations for the time period 2001-2014 is studied. These stations are located at the same geographic longitude and at different geographic latitudes and consequently different threshold rigidity (Fig. 2). Additionally, the diurnal anisotropy of cosmic ray intensity during the different phases of the last solar cycles 23 and 24, is also discussed.

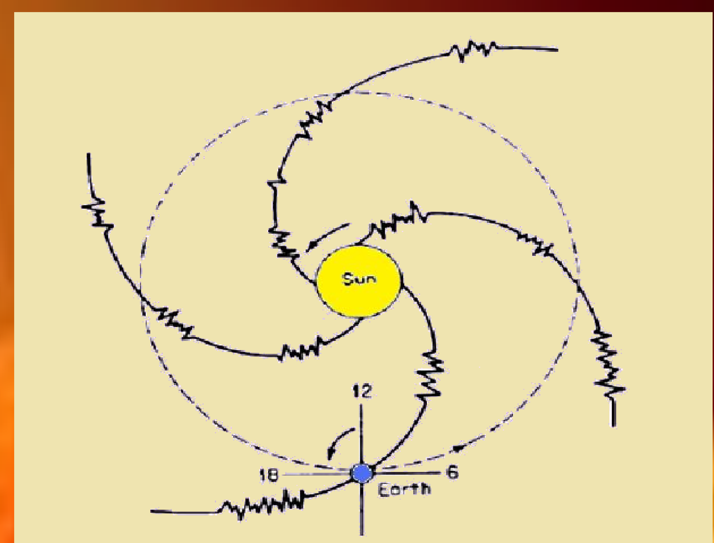
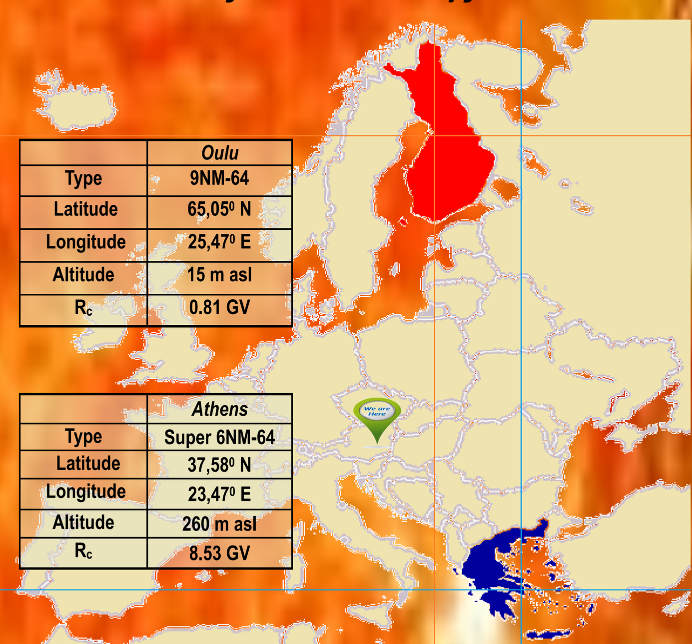


Figure 1: A graphical representation of the cosmic ray diurnal anisotropy.



	Oulu
Type	9NM-64
Latitude	65,05⁰ N
Longitude	25,47⁰ E
Altitude	15 m asl
R_c	0.81 GV

	Athens
Type	Super 6NM-64
Latitude	37,58⁰ N
Longitude	23,47⁰ E
Altitude	260 m asl
R_c	8.53 GV

Figure2: Characteristics of Athens & Oulu Neutron Monitor Stations

2. Data Analysis

Hourly corrected for pressure and efficiency values of the cosmic ray intensity from the Neutron Monitor stations of the University of Athens ANEMOS (cut-off rigidity 8.53 GV, http://cosray.phys.uoa.gr/) and the University of Oulu (cut-off rigidity 0.81 GV, http://cosmicrays.oulu.fi/) have been used. The examined time period 2001-2014 covers the maximum and the descending phase of the solar cycle 23 and the ascending phase of the solar cycle 24 as well. The diurnal vectors are calculated for each day (amplitude and time of maximum) using Fourier analysis. Our data have been normalized according to the equation:

$$A = \frac{I - I_{mean}}{I_{mean}} 100(\%)$$

where I_{mean} is the average cosmic ray intensity for each day and A is the percentage variation of the amplitude of the diurnal anisotropy. The calculated diurnal vectors are presented on a harmonic dial on monthly and annually basis *(Mavromichalaki, 1989)*.

3. Annual distribution of the diurnal anisotropy

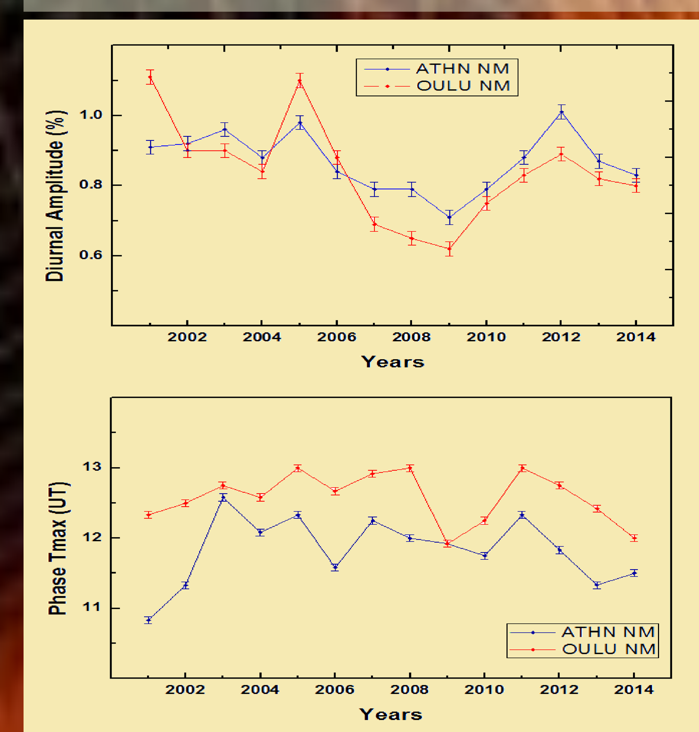


Figure 3: The profile of the amplitude (upper panel) and the time of maximum (lower panel) of the diurnal anisotropy for the years 2001-2014 is illustrated. It is observed that the diurnal amplitude follows the 11 -year variation of the solar cycle, while it is not valid for the diurnal phase (Tiwari et al., 2012). It is known that the solar magnetic field (SMF) reverses at each solar maximum activity. In our case the reversal of the SMF from positive to negative polarity was done at 2001 and from negative to positive at 2013. This confirms that the phase remains constant during the same polarity of SMF. Normally , two components are present in the anisotropy, one in the co-rotation direction and one radially outward from the sun (radial anisotropy).

	Athens NM			Oulu NM	
Date	A (%)	T_{max} (UT)	T_{max} (LT)	A (%)	T_{max} (UT)
2001	0.91±0.02	10.83±0.05	17.23±0.05	1.11±0.02	12.33±0.05
2002	0.92±0.02	11.33±0.05	17.73±0.05	0.90±0.02	12.50±0.05
2003	0.96±0.02	12.58±0.05	18.98±0.05	0.90±0.02	12.75±0.05
2004	0.88±0.02	12.08±0.05	18.48±0.05	0.84±0.02	12.58±0.05
2005	0.98±0.02	12.33±0.05	18.73±0.05	1.10±0.02	13.00±0.05
2006	0.84±0.02	11.58±0.05	17.98±0.05	0.88±0.02	12.67±0.05
2007	0.79±0.02	12.25±0.05	18.65±0.05	0.69±0.02	12.92±0.05
2008	0.79±0.02	12.00±0.05	18.40±0.05	0.65±0.02	13.00±0.05
2009	0.71±0.02	11.92±0.05	18.32±0.05	0.62±0.02	11.92±0.05
2010	0.79±0.02	11.75±0.05	18.15±0.05	0.75±0.02	12.25±0.05
2011	0.88±0.02	12.33±0.05	18.73±0.05	0.83±0.02	13.00±0.05
2012	1.01±0.02	11.83±0.05	18.23±0.05	0.89±0.02	12.75±0.05
2013	0.87±0.02	11.33±0.05	17.73±0.05	0.82±0.02	12.42±0.05
2014	0.83±0.02	11.50±0.05	17.90±0.05	0.80±0.02	12.00±0.05

Table I: Mean annual values of amplitude and phase of the diurnal anisotropy for Athens and Oulu stations.

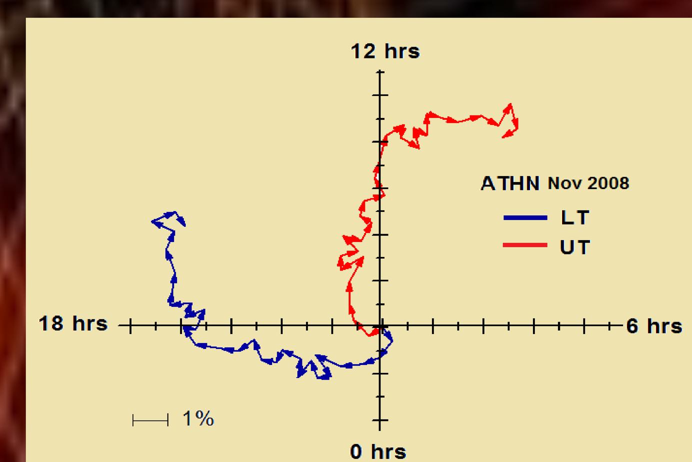


Figure 4: The daily diurnal vectors of Athens cosmic ray data in LT and UT during November 2008 are presented. Results are consistent with the co-rotational model, which supports the average diurnal amplitude along the 18 hrs (LT) direction. For Greece it applies: LT = UT + 2 + 4.4 where the term 2 represents the correction for UT to LT and the factor 4.4 is the correction due to geomagnetic bending, as the asymptotic cone for Athens is 66⁰ to the west of its geographic longitude (Mavromichalaki, 1989).

4. Monthly diurnal anisotropy during the different phases of the solar cycles 23 & 24

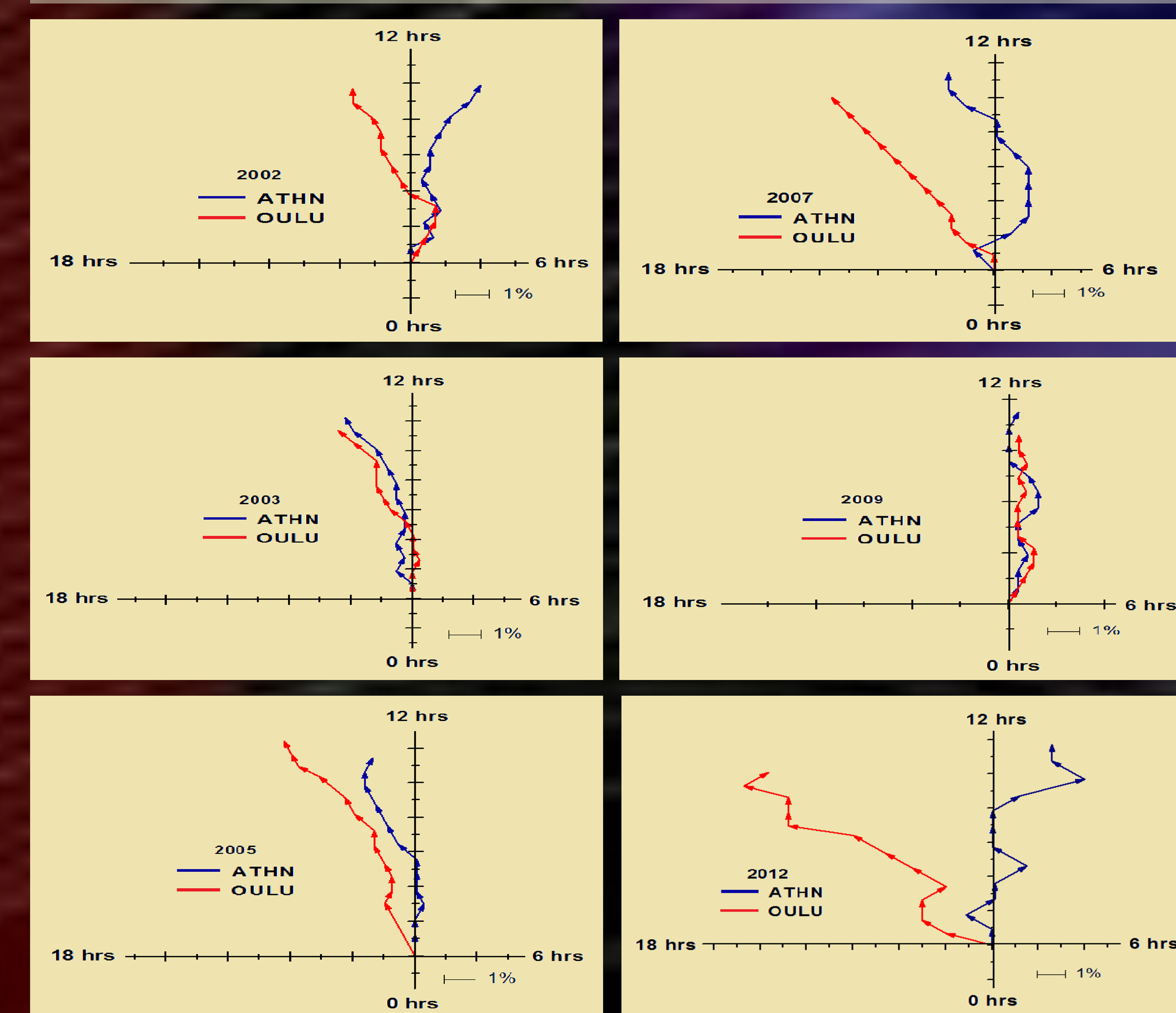
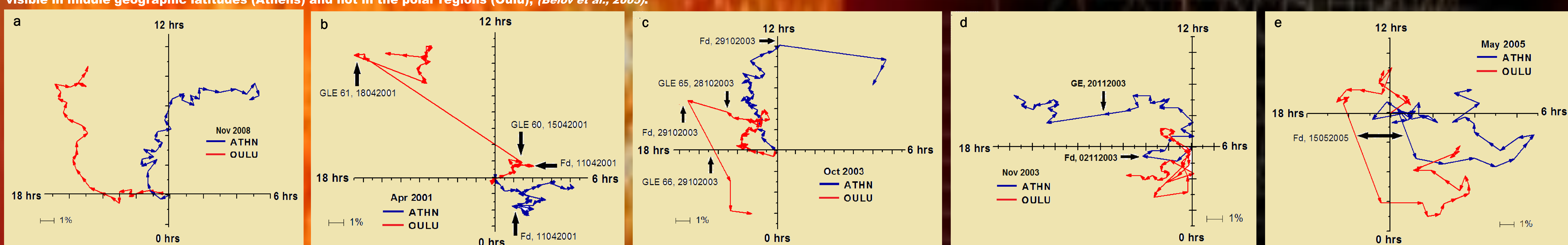


Figure 5: The monthly diurnal anisotropy vectors for Athens and Oulu stations for selected years are presented. A short term phase shift is observed during the descending phase of the solar cycle 23 and the ascending phase of the solar cycle 24. A phase shift to earlier hours during the solar cycle minimum (2009) is observed for both stations (Agrawal and Mishra, 2008). The phases are almost the same for 2009 (Mailyan and Chilingarian, 2010).

5. Typical examples of cosmic ray intensity diurnal anisotropy during quiet and disturbed time periods

The cosmic ray intensity modulation also includes many cosmic ray variations that affect the diurnal variation. The most important of them are the Ground Level Enhancements (GLEs), the Forbush decreases and magnetospheric events. The Ground Level Enhancements (GLEs) of cosmic ray intensity occur when a solar flare accelerates protons to sufficiently high energies for these particles to propagate along the heliomagnetic field to the Earth and be detected as a sharp increase in the counting rate of a ground based cosmic ray detector *(Plainaki et al., 2005)*. A Forbush decrease is a sudden and rapid decrease in the intensity of the galactic cosmic ray component with duration of about one week, which is due to strong solar events such as solar flares and coronal mass ejections *(Lingri et al., 2013)*. A magnetospheric event is also a sharp increase of cosmic ray intensity due to the influence of the geomagnetic field of the Earth. As a result, they become visible in middle geographic latitudes (Athens) and not in the polar regions (Oulu), *(Belov et al., 2005)*.



a. The diurnal vectors for November 2008 (quiet month) in a harmonical dial for both stations is presented.

b. In April 2001, a reversal of the diurnal anisotropy vector for both stations is observed during the Forbush decrease of April 11, 2001. The GLE60 and GLE61 are observed only by Oulu, as a near polar station. Nevertheless, great disturbances in the diurnal anisotropy are also observed at Athens.

c. In October 2003, one of the most astonishing Halo CMEs ("Mother of all Halos") took place on the 28/10/2003, provoking a GLE and a series of Forbush decreases. The GLE is recorded by the neutron monitor station of Oulu, while the Forbush decrease (recorded with an amplitude of 21% in Athens), causing a strong phase reversal, is evident by both stations.

d. During the magnetospheric event of November 2003 in Athens, a variation in the amplitude by 7% was recorded by the neutron monitor in Athens and Aurora was visible even from lower latitudes. This event was not visible from the neutron monitor of Oulu.

e. In May 2005, a change in the direction of the diurnal anisotropy vector is observed, resulting in strong fluctuations and loops, due to the Forbush decrease of May 11, 2005.

6. Conclusions

From the above analysis the following are outlined:

1. The diurnal time of maximum is observed to be around 12 hrs in UT for both stations, Athens and Oulu, whereas the diurnal amplitude is bigger in high latitudes-Oulu comparing to middle ones-Athens *(Mailyan and Chilingarian, 2010)*.
2. The annual diurnal amplitude follows the 11-year variation of the solar cycle, while the same doesn't seem to occur with the diurnal phase. This is consistent with the results of *Tiwari et al. (2012)*, which support the correlation with the 11-year solar cycle, while it is suggested that the diurnal phase varies with a period of 22 years (one solar magnetic cycle). The radial anisotropy vanishes during negative IMF polarity resulting in a phase shift to earlier hours *(Ahluwalia, 1988)*. In our case there is no evidence for a systematic phase shift on large scale for both stations for the examined period *(Tiwari et al., 2012)*.
3. A short term phase shift during the descending phase of the solar cycle 23 and the ascending phase of the solar cycle 24 is observed (Fig. 5). The time of maximum is identical for both stations during the minimum (year 2009).
4. The amplitude of the cosmic ray diurnal variation shows a great increase during GLEs, which is only observed by high amplitude neutron monitor stations.
5. During Forbush decreases, variation in the phase is observed by both stations, expressed as a reversal or a change in direction of the diurnal vector, resulting in fluctuations and loops, as the flux of cosmic radiation is not constant during the rotation of the Earth around its axis. These results are consistent with the diffusive-convective mechanism *(Ahluwalia, 1988)*. Loops and reversals during Forbush decreases are evident in both high and middle latitude stations.
6. Magnetospheric events are mainly observed in middle latitude stations, followed by a great increase in the cosmic ray diurnal amplitude, similar to the one observed in high latitude stations during GLEs.

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