PROCEEDINGS OF SCIENCE
ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany 37th International Cosmic Ray Conference 12–23 July 2021

Behaviour of different periodicities in galactic cosmic particles as observed by ACE during solar cycles 23 and 24

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Abstract:

Periodicities in O and Fe galactic cosmic particles at different energies as observed by the ACE satellite between 1997 and 2019 have been analyzed using various spectral analysis techniques. Daily mean energetic particle measurements are used to identify how several harmonics of the ~ 27-day synodic rotation period change during each individual year. Lomb-Scargle and Morlet wavelet spectral analysis of galactic cosmic particle data at different energies revealed in particular that the fourth harmonic (~7-day) of the solar rotation period occurs exceptionally strong during the minimum of solar cycle 23 (2008, 2009) when A< 0 (solar dipole pointing South) in comparison to the minimum of cycle 24 (2018,2019) when A> 0 (solar dipole pointing North). We report the presence of both the Rieger (~ 156 days) as well as the ~ 1.3-year periodicity in O and Fe GCR particles at various energies ranging from ~ 80 MeV/n to ~ 500 MeV/n.

37 International Cosmic Ray Conference -ICRC 2021
The Astroparticle Conference
12-23 July
Berlin, Germany

PoS(ICRC2021)1260

1. Introduction

Galactic cosmic rays (GCRs) consist predominantly of energetic electrons and nuclei originating from far beyond the solar system. They obtain their energies by shock wave-acceleration from supernova explosions. Energetic cosmic ray particle data from the Cosmic Ray Isotope Spectrometer (CRIS) [1] on board the *Advanced Composition Explorer* (*ACE*) spacecraft, located in a halo orbit about the L1 Lagrangian point. CRIS is designed to measure the nuclear charge, mass, and incident energy of cosmic rays. It has been providing data on the elemental and isotopic composition of ions from He to Ni ($2 \leq Z \leq 28$) at energies between ~50 and ~550 MeV/nucleon since it's deployment in space. A previous investigation [2] using galactic cosmic ray data from ground-based neutron monitor instruments that in particular the 4th harmonic of the ~ 27-day synodic rotation period exhibits a completely different behaviour during intervals when the solar magnetic dipole is pointing South (A<0) in comparison to intervals when the solar dipole is pointing North (A>0). It has also been found that in particular during the minimum of Cycle 23 (2009, early 2010) that the solar modulation of the cosmic rays was less pronounced than during any previous solar minimum since the start of the space age [3]. GCR data obtained during this interval are therefore less affected by solar modulation than any previous measurement at similar energies near Earth [4]. In this paper we apply Lomb-Scargle as well as Morlet wavelet spectral analysis techniques to daily mean GCR data from two different elements, Fe and O, as measured by the CRIS instrument on the ACE satellite (http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_CRIS.html). The main aim is to investigate possible time- as well as energy -dependent behaviour of different periodicities in these GCR particles during Cycles 23 and 24.

2. Results and Discussion

2.1 27-day Periodicity and its Harmonics

Several studies in the past have been done to investigate the higher harmonics of the ~ 27-day galactic cosmic ray (GCR) variations, particularly the second (~14-day) as well as the third (~9-day) harmonic [5]. The general conclusion from these investigations is that the origin of the higher harmonics, particularly the 14-day and 9-day periodicities is the simultaneous existence of active regions on the solar surface at different longitude positions [6] as well as the the presence of large-scale structures present in the heliosphere during solar minimum intervals. Studies by Gil and Mursula [7] determined that the amplitudes of the ~27-day variation of the GCR intensity by neutron monitors are indeed larger during the minimum epochs of solar activity for the A>0 compared to conditions when A<0. This particular behaviour of the ~ 27-day period has also been confirmed by our investigation using GCR data from the ACE satellite. Figure 1 below shows a Lomb-Scargle periodogram of Fe (150.4 MeV/n) during 2008 and 2018.

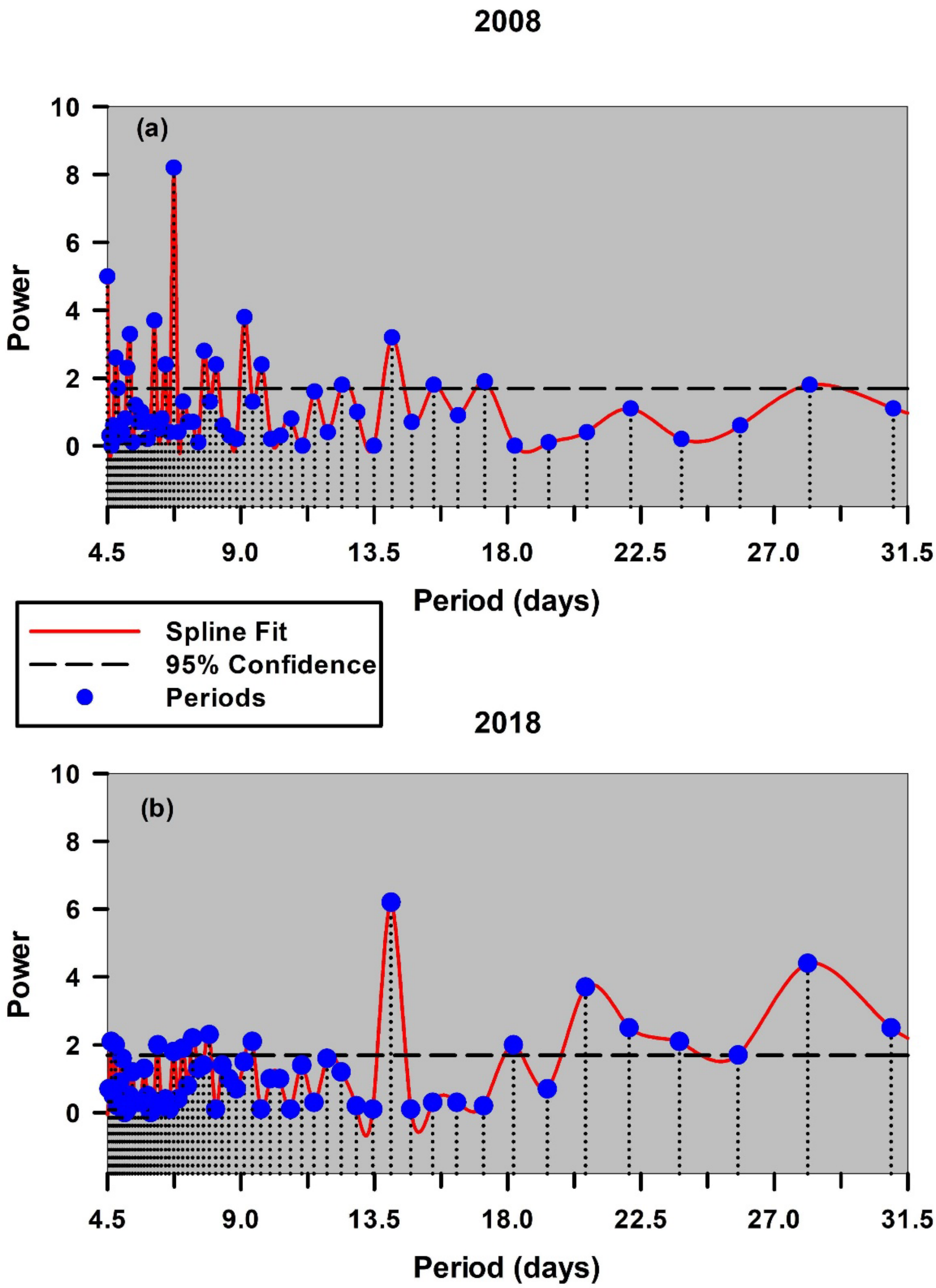

Figure 1. Lomb-Scargle periodogram of Fe (150.4 MeV/n) during 2008 (a) and 2018 (b) showing the power of different harmonics of the ~ 27-day periodicity.

An analysis of Figure 1(a) reveals exceptionally strong ~ 7-day periodicity in the Lomb-Scargle periodogram of Fe at 150.4 MeV/n during 2008 while the ~ 27-day period is marginally above the 95% confidence level. The solar minimum interval of Cycle 23 from 2006 to 2009 is a period characterised as A<0 when the solar magnetic dipole is directed South. In contrast, Figure 1(b) shows very little ~ 7-day activity in the periodogram, while the ~ 27-day period and ~ 14-day (second harmonic) periods during 2018 show strong power levels well above the 95% confidence level. During the minimum of Cycle 24 (2017-2019) the solar magnetic dipole is directed North and is a period characterised as A>0. A Morlet wavelet analysis during 2008 (Figure 2) and 2018 (Figure 3) confirm the Lomb-Scargle results in Figure 1.

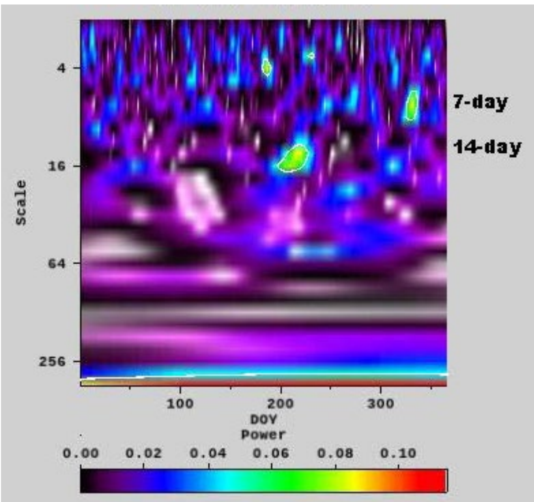

Figure 2. A Morlet wavelet analysis of Fe (150.4 MeV/n) during 2008 showing only the ~ 7-day and ~ 14-day periodicities above the 95% confidence level (indicated by the white contour line)

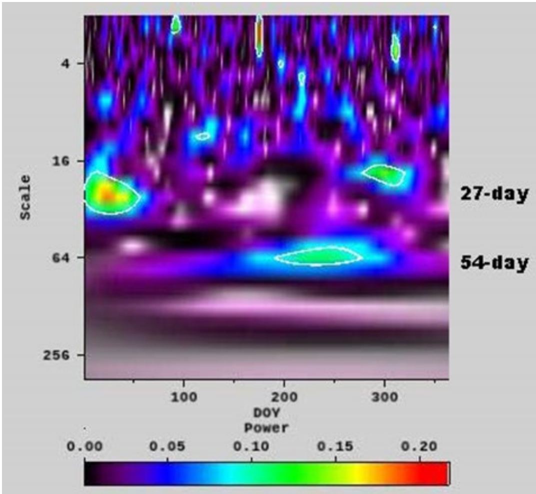

Figure 3. A Morlet wavelet analysis of Fe (150.4 MeV/n) during 2018 showing only the ~ 27-day and ~ 54-day periodicities above the 95% confidence level (indicated by the white contour line).

We subsequently performed Lomb-Scargle spectral analysis for both O and Fe between 1998-2019 for every individual energy band of data as measured by CRIS. This enabled a study of the power of each periodicity as a function of energy. Figures 4 (a) and (b) below show results obtained for the different harmonics of the ~ 7-day periodicity for both O and Fe at various energies.

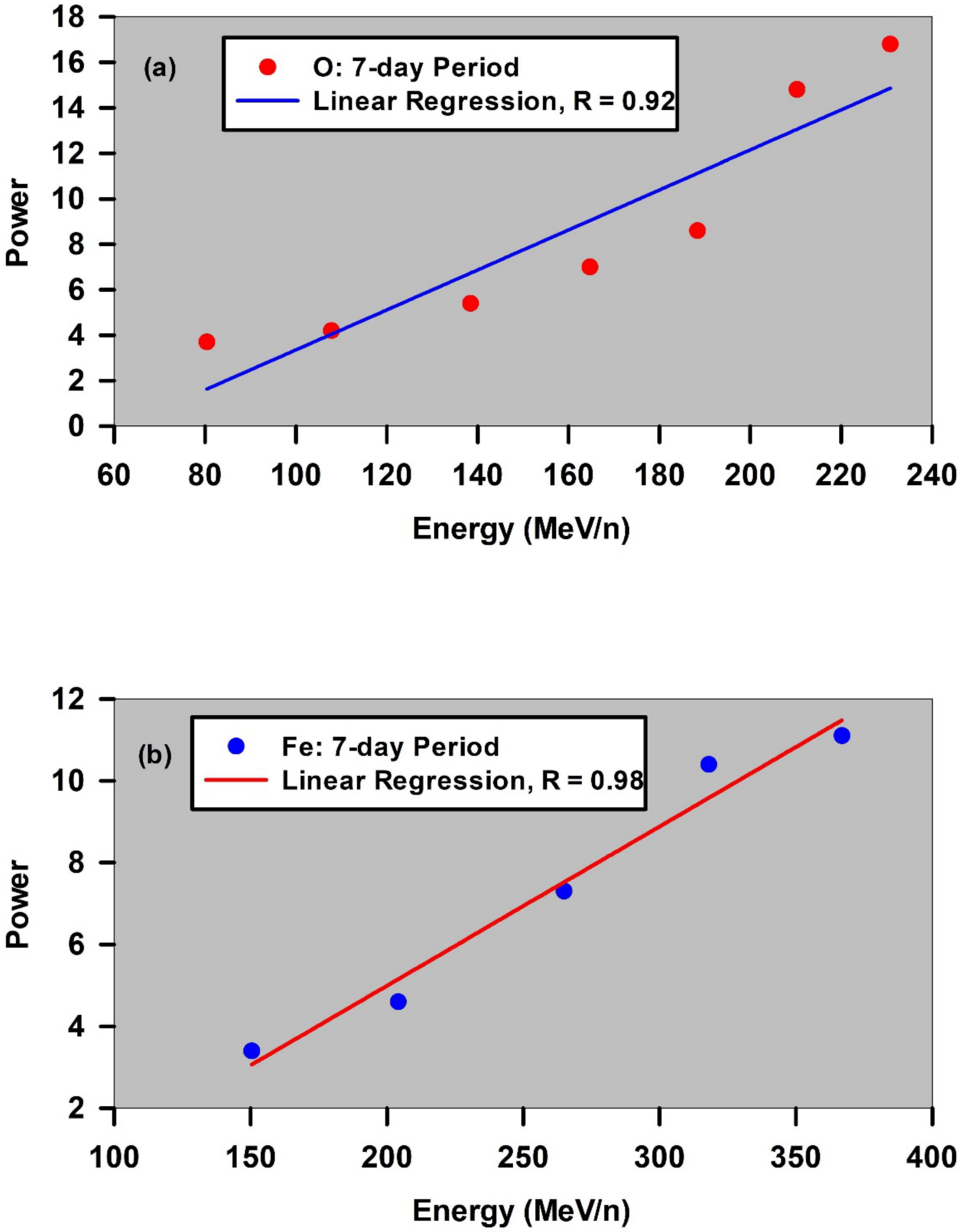

Figure 4. A plot showing the power of the 7-day periodicity for oxygen (a) and iron (b) GCR particles as a function of energy as determined by the Lomb-Scargle periodogram method.

A clear energy-dependence tendency for the 7-day periodicity can be observed in Figure 4. The power of the periodicity increases with increasing energy as revealed by the respective linear regression fits for both O and Fe. This tendency shows that in particular the 7-day periodicity in O and Fe GCR particles is more sensitive to higher energies. This is a new finding which has not been reported before in the literature.

2.2 Rieger and 1.3-year Periodicity

Recent investigations on helioseismic data [8] showed that both the Rieger periodicity around ~ 155-day as well as the ~ 1.3-year periodicity have a common origin which can be linked to the solar magnetic dynamo. We therefore extended our investigation to determine whether these two characteristic periodicities of the solar magnetic field could also be found in the modulation of energetic galactic cosmic particles like O and Fe. A Lomb-Scargle periodogram for Fe at 150.4 MeV/n for the time interval 1997-2019 can be seen in Figure 5.

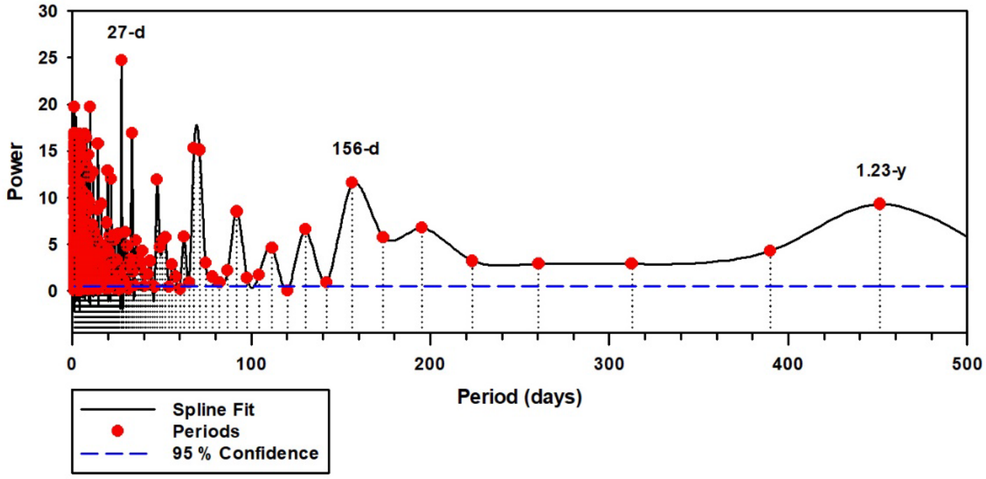

Figure 5. Lomb-Scargle periodogram for Fe GCR at 150.4 MeV/n during 1997 – 2019

From Figure 5 the presence of the Rieger periodicity at ~ 156 days as well as a period at 1.23 years are detected above the 95% statistical confidence level. A Lomb-Scargle periodogram of oxygen GCR particles at 107.8 MeV/n also revealed the presence of both the Rieger periodicity at ~ 156 days as well as a periodicity at 1.32 years, slightly different to iron GCR particles at the same energy. Results for oxygen are shown in Figure 6 below.

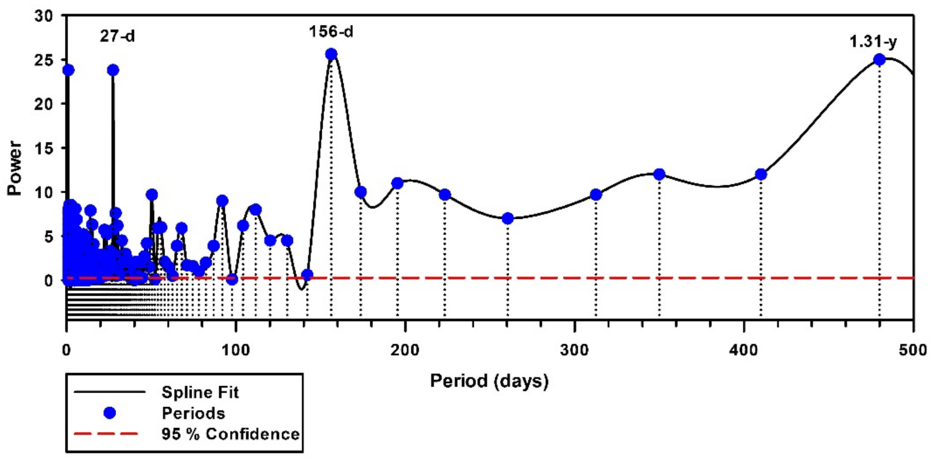

Figure 6. Similar to Figure 5, but for oxygen GCR particles at 107.8 MeV/n.

A Lomb-Scargle spectral analysis was subsequently performed at each of the 7 energy intervals as measured by the CRIS instrument (Stone et al., 1998) for both O and Fe for every annual interval consisting of daily mean values between 2000 and 2019. This was done to investigate the temporal behaviour of the Rieger periodicity at ~ 155 days during different phases of both solar cycles 23 and 24. Only results above the 95% confidence level were recorded and are shown below for O in Figure 7.

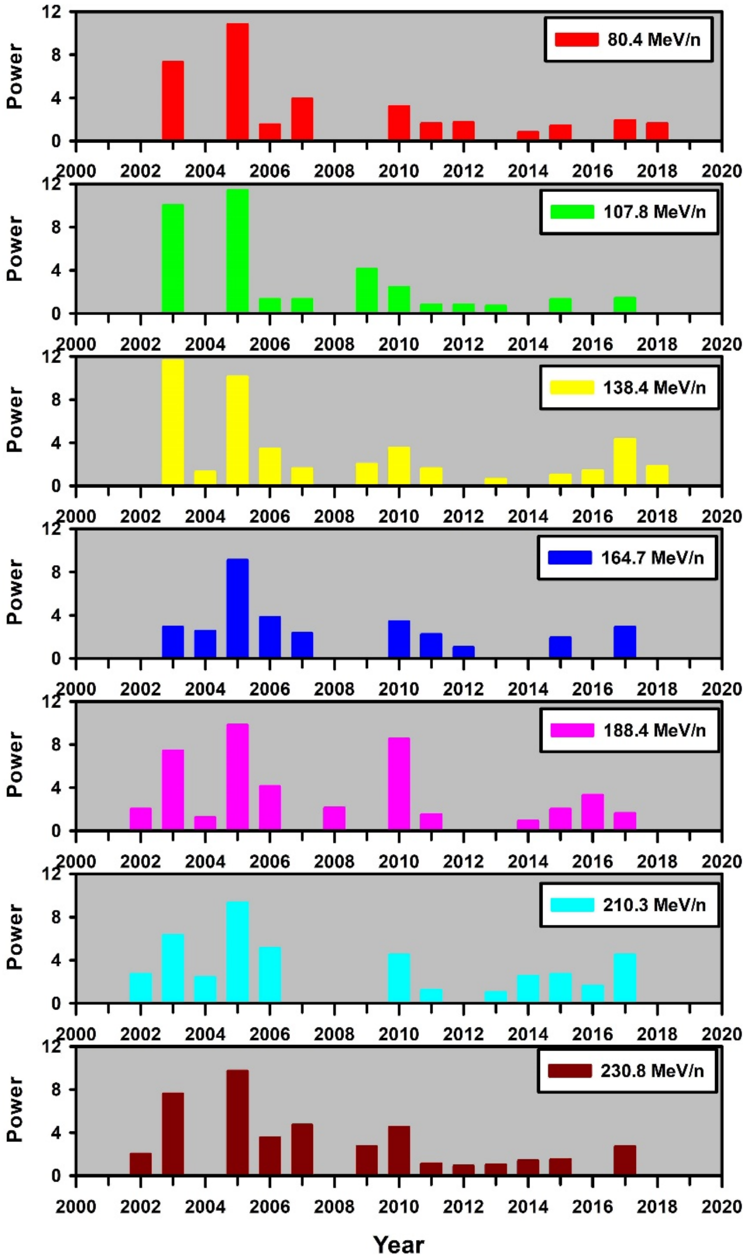

Figure 7. Oxygen Rieger periodicity at different energies as obtained by Lomb-Scargle spectral analysis at each individual year from 2000 to 2019. Only results above the 95% confidence level are shown. Energies indicated refer to the center point of each energy interval as measured by the CRIS instrument onboard ACE.

From Figure 7 one can clearly see that the strongest Rieger periodicities occur during solar cycle 23, with the strongest occurrence during 2005 at all energies ranging from ~ 70 MeV/n to ~ 238 MeV/n. It is also evident that during the minimum of both Cycle 23 (2008-2009) and Cycle 24 (2018-2019) that the Rieger period is extremely weak or below the 95% confidence level. These findings are in line with the observed strong presence of the 27-day synodic periodicity and its different harmonics when the solar dipole points South (A < 0) during Cycle 23 in contrast to a dipole orientation characterised by A

> 0 (pointing North) during Cycle 24.

3. Conclusions

During particularly solar minima with negative polarity GCR's drift preferentially inward towards the Sun along the heliospheric current sheet [7,9]. The wavy current sheet as well as the more variable structure of the solar wind during these intervals are most probably responsible for the strong observation of 7-day periodicities when A<0 in comparison to solar dipole orientations characterised by A>0. In addition, the influence of co-rotating interaction regions during A<0 solar minima intervals should also be taken into account. In contrast during solar minima when A>0, the heliolatitudinal variation of the solar wind is a more important factor responsible for GCR's to encounter faster solar wind streams with less variable structures, and hence less power in the fourth harmonic activity.
In their analysis of sunspot data Krivova and Solanki [8] pointed out that the Rieger as well as the 1.3-year periodicity have their origin in the solar dynamo. In contrast to previous investigations we report for the first time the presence of both the ~ 156-day as well as the ~ 1.3-year periodicity in O and Fe GCR particles at different energies.

The results obtained in this investigation showed that galactic cosmic particles as observed by the ACE satellite exhibit peculiar short-term periodicity behaviour as a result of solar polarity dependent magnetic drifts during a negative minimum which is in line with previous results using neutron monitor data from Hermanus and Jungfraujoch [2]. Chowdhury et al. [10] also recently made an extensive time series analysis of different solar and interplanetary and NM data for the first five years of Cycle 24 and detected a statistically significant presence of both the Rieger-type (150 – 160 days) and the ~ 1.3-year periods during this epoch. We also report for the first time that the 4^{th} harmonic of the ~ 27-day solar rotation period (~ 7-day period) for both O and Fe GCR particles as measured by the ACE satellite exhibit a linear relation with energy.

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PoS(ICRC2021)1260