International Journal of Scientific Research in Science and Technology
Print ISSN: 2395-6011 | Online ISSN: 2395-602X (www.ijsrst.com)
doi : https://doi.org/10.32628/IJSRST

Effect of Solar Output on Semi-diurnal Anisotropy of Cosmic Ray Intensity

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Article Info
Volume 9, Issue 3
Page Number : 199-218

Publication Issue
May-June-2022

Article History
Accepted : 01 May 2022
Published : 12 May 2022

ABSTRACT

Using the experimental data of the high counting rate neutron monitors, the semi-diurnal anisotropy of cosmic ray intensity has been investigated for the period 1965 – 2014 (solar cycles 20 to 24). The semi-diurnal amplitude shows negative correlation with the diurnal amplitude for the period 1965-2014, which may be due to the presence of significant modulation of semi-diurnal anisotropy with periods of 22 year sunspots magnetic cycle. For the semi-diurnal anisotropy, the phase is evenly distributed in the first and second quadrant. Observed semi-diurnal phase is maximum (~10h) during minimum phase of positive polarity (A>0). We also notice that in the even solar cycles (20 & 22) the annual average of semi-diurnal amplitude is generally maximum (near the solar activity minima) in its declining phase which are associated with high values of solar wind velocity and high values of semi-diurnal amplitude are observed during these periods. In contrast, the semi-diurnal amplitude is minimum in the declining phase (near the solar activity maxima). To highlight the effect, the average semi-diurnal amplitude and phase has been calculated (i) by grouping the years separately for solar cycles 20, 21, 22 ,23 & 24 as well as (ii) on the basis of polarity states of the solar magnetic field (A>0) is very significantly different from the other polarity state (i.e. A<0).

Keywords: Daily variation of cosmic ray intensity, neutron monitor, solar cycle, solar magnetic cycle.

I. INTRODUCTION

Daily variations in cosmic ray intensity arise from the spatial anisotropies in interplanetary space. These are recorded by ground based detectors is subjected to the solar semi-diurnal variation of extraterrestrial origin (i.e. Rao and Sarabhai, 1961; Ahluwalia, 1962; Ables, et.al.,1965; Quenby and Lietti,1968; Rao and Agrawal,1970). The component of the daily variation corresponding to two cycles per day is known as semi-diurnal variation. With the availability of the data from super neutron monitors having high statistical significance, Ables et.al. (1965), for the first time, had conclusively showed the existence of semi-diurnal component of solar daily variation of worldwide nature. The average characteristics of the semi-diurnal variation are represented by the equation:

$$\frac{\Delta J(R)}{J(R)} = A\, g(\wedge)\, R\, \beta \qquad \text{for } R < R_{max}$$

$$= 0 \qquad \text{for } R > R_{max}$$

Where g ($\wedge$) describes the dependence of anisotropy on declination and "R" shows the dependence of anisotropy on rigidity, 'A' denotes amplitude. The value of β has been estimated ~ 1.0 to 1.2 and g ($\wedge$) = $\cos^2\wedge$. (Ables et. al,1965)

The variation is due to the second-order anisotropy produced by the diffusion convection of cosmic rays in interplanetary space (i.e. Quenby and Lietti, 1968; Munakata and Nagashima, 1986). The observed amplitudes of the solar semi-diurnal variation of cosmic rays is proportional to the solar activity and is about $\approx$0.05%, on average which is a factor of 5 to 6 less than that for the diurnal amplitude(Quenby and Lietti, 1968; Fujii et.al.,1971). The time of maximum of the semi-diurnal anisotropy is $\approx$ 3 hours in space, a direction which is essentially perpendicular to the average direction of the interplanetary magnetic field at one astronomical unit (1 AU) (Ables et al., 1965; Rao and Agrawal, 1970;Kumar et.al.,1981). The variation depends on polarity state of the polar magnetic field of the Sun, that is, the variation changes its phase for the transition of the polarity state from "positive" to "negative" or vice versa, which occurs every epoch of the maximum solar activity (Nagasmima et.al.,1986; Tiwari et.al.,2012; Sabbah 2013). The state is defined as "positive", when the magnetic field is away from the Sun at the North Pole and toward the Sun at the South Pole , while it is called " negative" when the polar magnetic fields are reversed. According to the theoretical investigation by Munakata and Nagashima (1986), the polarity dependence of the phase change has been interpreted as a result of the change of the cosmic ray density distribution in space caused by the difference of cosmic ray drift motion in the positive and negative polarity states (Jockipii et.al.,1977; Ahluwalia and Fikani, 1996 and b). Singh et.al, (2010) found that the high amplitude events (HAE) appear quite dominantly during the declining phase, as well as near the maxima of the solar activity cycle and the low amplitude events (LAE) are inversely correlated with solar activity cycle. Sabbah (2011) found that the wavelet spectrum density in the vicinity of the second and third harmonic of the 27 day variation weakly correlations with BV^2 with better correlation for the third harmonic.

II. Data Analysis

The available hourly pressure corrected neutron monitor data of Kiel and Moscow obtained from websites
ftp://ftp.ngdc.noaa.gov/stp/solar_data/cosmic_ray,
have been subjected to harmonic analysis to derive the semi- diurnal amplitude (in %) and semi-diurnal phase (in hours), for an overall period of 50 years, during the years 1965-2014 . These neutron monitor stations are so selected that they cover the major part of the earth's location. Certain days associated with universal time changes, such as Forbush decreases and large cosmic ray transient intensity variations are removed from the basic data, before calculating the average amplitude and phase for each year data and for each station. Fourier analysis has been found to be the most suitable way for the study of daily variation of the cosmic ray intensity. The amplitude and phase of the first and second harmonics of the daily variation are calculated by noting the hourly count rate of the observed cosmic ray intensity (Chapman and Bartels, 1940). However, it implies the assumption that the variation is constant for at least 24 hours. The method of power spectral analysis has been also used by different investigators for the study of daily variations of the cosmic ray intensity. Earlier, many authors had investigated and deduced the characteristic properties of only the first and second harmonics of the daily variation i.e., the diurnal and

semi-diurnal variation of the cosmic ray intensity. As such, by one or the other method, the information regarding the amplitude and time dependence of the daily variation of the cosmic ray intensity, can be easily obtained by performing the simple harmonic analysis on the hourly data.

Time dependent harmonic function of f(t) with 24 equidistant point in the interval from

t = 0 to t = 2π can be expressed in terms of Fourier series:

$$Y = f(t) = a_0 + \sum_{n=1}^{24} (a_n \cos nt + b_n \sin nt)$$

$$f(t) = a_0 + \sum_{n=1}^{24} r_n \cos(nt - \phi_n)$$

Where, a_o is the mean value of f(t) for the time interval from 0 to 2π and a_n, b_n are the coefficient for the n^{th} harmonics which are written as follows:

$$a_o = 1/24 \sum_{i=1}^{24} r_i$$

$$a_n = 1/12 \sum_{i=1}^{24} r_i \cos nt_i$$

$$b_n = 1/12 \sum_{i=1}^{24} r_i \sin nt_i$$

where r_i is a hourly cosmic ray intensity for 24 points,

$r_n \cos(nt - \phi_n) = a_n \cos nt + b_n \sin nt$.

The amplitude r_n and phase ϕ_n of the n^{th} harmonic can be expressed as:

$$r_n = (a_n^2 + b_n^2)^{\frac{1}{2}}$$

$$\phi_n = \tan^{-1}(b_n/a_n)$$

The daily variation of the cosmic ray intensity can be adequately represented by the superposition of first, second, third and fourth harmonics as follows:

$f(t_i) = a_1 \cos t_i + b_1 \sin t_i + a_2 \cos 2t_i + b_2 \sin 2t_i + a_3 \cos 3t_i + b_3 \sin 3t_i + a_4 \cos 4t_i + b_4 \cos 4t_i$

By assuming that the hourly values follow a standard Gaussian distribution; the standard errors in the determination of the various harmonics are given as follows:

$$\sigma a_n^2 = \sigma b_n^2 = \sigma r_n^2 = \sigma 2/12$$

and $\sigma \phi_n = \sigma r_n / r_n$

Where 'σ' is the standard error associated with the hourly count rate of cosmic ray intensity data for any station and where r_n and ϕ_n are the amplitude and phase of the n^{th} harmonic. The derived values for each day (through a comprehensive computer code written in Visual Basic) can then be used on each day basis, or can be vectorially averaged over a certain period. These can then be diagrammatically represented either by a simple vector addition diagram or by a 360^0 harmonic dial, or both. Such a harmonic dial and the vector addition diagram for the average harmonic analysis. The semi-diurnal anisotropy (second harmonics of daily variation) vectors have been examined by plotting their observed averages on the harmonic dial, and in the form of vectors addition diagram, after classifying them annually and also averaging them into appropriate groups according to different solar cycles, 1965-1976(20), 1976-1986(21),1986-1996(22),and 1996-2008(23), as well as on the basis of polarity states of the solar magnetic field, 1965-1969 (A<0), 1971-1979(A>0), 1981-1989(A<0),1991-2000(A>0) and 2002-2014(A<0). The recent solar, interplanetary and geomagnetic activity index (Ap) parameters are taken from websites http://omniweb.gsfc.nasa.gov.

III. Discussion and Results

Each day vectors of the daily cosmic rays variation are vectorially added to provide the average values including the annual average. To monitor the vectorial changes from one year to another, it is useful to plot the values in vector form. In fact, these average are generally studied by depicting them either as a harmonic dial representation and in vector addition format. In figure 1, we shows the vector addition diagram of annual average vectors of the second harmonic of the daily variation of cosmic rays, for the Moscow neutron monitor station for the years 1965-2014 (solar cycles 20-24) and Kiel neutron monitor station for the years 1965-2008. From this figure, it is very clearly noticed that the semi- diurnal phase has continuously shifting to earlier and later hours in different phases of solar cycles. The overall average semi-diurnal vectors for the Kiel and Moscow neutron monitor stations have also been deduced and these are found to be:

Moscow: r_2 (1965-2014) = (0.033±0.0004)%, ϕ_2=(0.87±0.044)hours.

Kiel: r_2 (1965-2008) = (0.029±0.0004)%, ϕ_2 = (0.57±0.046) hours,

We have presented the data together in figure 1 to show the differences (if any) in the variation of semi-diurnal variation from two similar high latitude stations (Kiel and Moscow) and to bring out the observed similarities between the two high latitude stations, Kiel and Moscow. As such, we can select any one station for further analysis, as both stations are running parallel to each other. The enhancements in the average solar wind speed during the declining phases of the solar cycles may also be responsible for the increase in amplitude of the diurnal and semi-diurnal anisotropy (Figure 2 a &b). Figure 2 shows the annual average values of solar wind speed (V), geomagnetic activity index (Ap), sunspot number(R), interplanetary magnetic field (B) and modulation parameter (V.B). The solar wind speed is highest during the declining phase of solar cycle (1973-1975, 1982-1984, 1993-1994, and 2003), it reached the highest value in 2003 and the lowest value in 2009. Solar wind speed, interplanetary magnetic field (B), modulation parameter (V.B) and geomagnetic index (Ap) are enhanced during the declining phase of solar activity (figure 2) semi-diurnal amplitudes are enhanced during the solar activity minima periods, from this figure shows that diurnal variation of cosmic ray intensity is better correlated with the modulation parameter (V.B) rather than with B alone and geomagnetic activity index (Ap) correlates much better with the magnitude of (V.B).where the years of solar activity minimum and maxima, for each cycle are also marked by vertical lines (dashed lines and full lines respectively). In figure 3, we have shown the harmonic dial representation of the yearly average vectors the second harmonic of the daily variation of cosmic rays for the Moscow neutron monitor station for the period of 1965-76 (Solar cycle 20). The Semi-diurnal phase is evenly distributed in the first and second quadrant, as clearly seen from this figure. Semi-diurnal phase shifted to later hours during minimum phase of positive polarity (A>0). Semi-diurnal amplitudes are maximum during the years 1965, 1966, 1973, 1975, 1976 and minimum during the years 1970 and 1972. The annual average vectors of the second harmonic of daily variation of cosmic rays are plotted in vector addition diagram(Figure 4) for the Moscow neutron-monitor station, for 1965-1976(Solar cycle 20). From this figure it is very clearly noticed that the semi- diurnal phase has continuously changing to earlier hours from 1965-1976(Cycle 20). Moreover, in the beginning the diurnal amplitude shows in decreasing trend. The overall average semi-diurnal vectors (amplitude r_2, phase ϕ_2) for the entire solar cycle 20 (1965-1976), for the Moscow station, has also been deduced and is found to be:

Moscow: r_2 (1965-76) = (0.0379±0.0011) %, ϕ_2= (1.13±0.087) hours.

Figure 5 shows the harmonic dial representation of the annual average vectors of the second harmonic of the daily variation of cosmic rays for the Moscow neutron monitor station, for the period of 1976-1986(Solar cycle- 21). From this figure, semi-diurnal phase is observed to be evenly distributed in the first and second quadrant which years 1976 and 1977; semi-diurnal phase is distributed in the second quadrant. Figure 6, shows the vector-addition diagram of annual- average vectors of the second harmonic of the daily variation of cosmic rays for the Moscow neutron-monitor station, for the years 1976-1986 (solar cycle 21). From this figure, the semi-diurnal phase has continuously shifting to later hours from 1976-1986 onwards. The semi-diurnal amplitude has a significantly increasing and decreasing trend throughout the study time period. The overall average semi-diurnal vectors, for the entire solar cycle 21(1976-1986), for the Moscow station is found to be:

Moscow: r_2 (1976-86) = (0.0259±0.0008) %, ϕ_2= (0.66±0.091)hours.

Figure7 shows the harmonic dial representation of the yearly average vectors of the second harmonics of the daily variation of cosmic rays for the Moscow neutron monitor station for the period of 1986-1996(solar cycle-22).From this figure, its revealed that the semi-diurnal phase is evenly distributed in the first and second quadrant, while in years 1991, 1995, 1996, semi-diurnal phase shifted to later hours (A>0) and semi-diurnal amplitude is larger during the declining and minimum phase of solar cycle, 22 (years 1988,1993, 1994, 1995, 1996). Figure 8, Shows the vector-addition diagram of annual- average vectors of the second harmonic of the daily variation of cosmic rays for the Moscow neutron-monitor station, for the years 1986-1996 (Solar cycle 22). Again, from this figure, it is observed that the semi-diurnal phase is continuously shifting to earlier hours beginning in 1986 and continuously shifting to the solar activity minimum (1996). However, no definite trend is seen in the variation of semi-diurnal amplitude except for the minimum value observed in 1990. The overall average semi-diurnal vectors, for the entire solar cycle 22(1986-1996), for the Moscow station is found to be:

Moscow: r_2 (1986-96) = (0.0301±0.0009) %, ϕ_2= (0.6±0.092) hours.

Figure 9 shows the harmonic dial representation of the yearly average vectors of the second harmonics of the daily variation of cosmic rays for the Moscow neutron monitor station for the period of 1996-2008 (Solar cycle-23). From this figure, it is observed that the semi-diurnal phase is evenly distributed in the first and second quadrant while again, in years 1996, 1997 (A>0), the semi-diurnal phase shifts to later hours and semi-diurnal amplitude is larger during the declining and minimum phase of solar cycle 23. Figure 10 shows the vector-addition diagram of annual- average vectors of the second harmonic of the daily variation of cosmic rays for the Moscow neutron-monitor stations, for the years 1996-2008 (solar cycle 23). This figure clearly shows that the semi-diurnal phase has continuously shifted to later hours during the years 1996, 1997 from the beginning of solar cycle 23. The overall average semi-diurnal vectors, for the entire solar cycle 23(1996-2008), for the Moscow station is found to be:

Moscow: r_2 (1996-08) = (0.0343±0.0007) %, ϕ_2= (0.8±0.091) hours.

In figure 11, we have shown harmonic dial representation of the yearly average vectors of the daily variation of cosmic rays for the Moscow neutron monitor station for the period of 2008-2014 (Ascending phase of solar cycle-24). The semi-diurnal amplitude, as clearly seen from this figure, is low during the years 2009 & 2014 and increases during the years 2008(Solar minima), 2011 and 2013. Figure 12 shows the vector-addition diagram of annual-average vectors of the second harmonic of the daily variation of cosmic rays in the ascending phase of solar cycle 24 (2008-2014) for the Moscow neutron-monitor station. From the figure, it is clearly evident that semidiurnal phase is shifted to later hours in the years 2008, 2012 and 2014. The overall average semi-diurnal vectors, for the ascending phase of solar cycle 24(2008-2014), for the Moscow station is found to be:

Moscow: r_2 (2008-14) = (0.0360±0.0009) %, ϕ_2=(0.5±0.012)hours.

To discuss the comparative variation of the average semi-diurnal anisotropy on the scale of a solar cycle ,the semi-diurnal vectors on the harmonic dial are shown, for the four complete solar cycles, 20 (1965-1976), 21 (1976-1986), 22 (1986-1996), 23(1996-2008) and ascending phase of solar cycle 24 (2008-2014) in figure 13 whereas in figure 14, for each A<0(1965-69, 1981-89, 2002-14) and A>0 (1971-79, 1991-2000) solar magnetic polarity epoch. When averaged vectorially over a complete solar cycle, we find systematic and significant differences between one cycle to another cycle. When averaged over a polarity state of the solar magnetic field (A<0 & A>0), the semi-diurnal amplitude are nearly same for the both polarity state, Semi-diurnal phase shifted to earlier hours ($0^0<\phi_2< 21^0$=0.7 h) during positive polarity state (A>0) as compared to overall average of negative polarity state (A<0) (24^0= 0.8 h $<\phi_2 < 90^0$=3 h).

IV. Conclusions

From the discussions of observations and results, we conclude that:

Annual average of semi-diurnal amplitude (r_2) is found to be minimum during solar activity maxima and is near maximum, near the solar activity minima time period, whereas the declining phase also in all the solar cycles taken into consideration (Solar cycles 20,21,22,23 and ascending phase of solar cycle 24), the increase in semidiurnal anisotropy of cosmic ray intensity near minima and declining phase of solar activity cycle, is due to high speed solar wind modulated to semidiurnal anisotropy. Previously, the long –term variation in the amplitude and phase of the semi –diurnal anisotropy has been studied for the epochs 1968-1979(Agrawal et.al., 1983) and 1968-1984 (Pathak & Agrawal, 1987), they also found an increase in the amplitude of the anisotropy during the years 1973-1974 during the declining phase of the solar cycle 20.

The solar wind speed is highest during the declining phase of solar cycle (1973-1975, 1982-1984, 1994-1995 and 2003) it reached the highest value in 2003 and lowest value in 2009. Solar wind speed (V), modulation parameter (V.B) and geomagnetic activity index (Ap) are enhanced during the declining phase of solar activity when the diurnal and semi-diurnal amplitude of cosmic ray intensity is increased. Solar wind speed produces significant deviation in semi-diurnal of cosmic ray intensity during declining and minimum phase of solar activity cycles.

Annual average semidiurnal amplitude varies in the very low range. It mostly varies in the range 0,.014% to 0.055% on the annual basis. The semi-diurnal phase is evenly distributed in the first (0 h to 3 h) and second (9 h to 12 h) quadrant of harmonic dial. Diurnal and semidiurnal phases are negative correlated during the minimum phase of the solar cycles.

Average solar cycle semi-diurnal amplitude are higher during the solar cycles (20, 23 & semi-cycles 24) compared to solar cycles (21, 22) and semi-diurnal phase shift to later hours during the averaged solar cycle (20, 23) compared to another solar cycles. Average over a polarity state of the solar magnetic field, the semidiurnal amplitude are nearly same for the both polarity state (A<0 & A>0), semidiurnal phase shifted to earlier hours during the positive polarity state (A>0) as compared to overall average of negative polarity state (A<0).

Solar cycle 24 (Ascending phase) is presenting peculiar deviation, while comparison of another solar cycles, the the interplanetary parameters (V, B, V. B) and geomagnetic activity index Ap all are near to the minimum level. The length of ascending phase of solar cycle 24 is also much larger while comparing with another solar cycles (20, 21, 22 and 23).We finds that diurnal and semidiurnal variation of cosmic ray intensity is better correlated with modulation parameter (V. B). Diurnal and semidiurnal phases are negative correlated during the minimum phase of the solar cycles.

Acknowledgement

The author are grateful to the research teams working in Moscow neutron monitor station, ACE/wind, OMNI, and NOAA data centers for providing the related data.

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Cite this article as :

Ambika Singh, "Effect of Solar Output on Semi-diurnal Anisotropy of Cosmic Ray Intensity", International Journal of Scientific Research in Science and Technology (IJSRST), Online ISSN : 2395-602X, Print ISSN : 2395-6011, Volume 9 Issue 3, pp. 199-218, May-June 2022.

Journal URL : https://ijsrst.com/IJSRST229270

Table 1 : List of Neutron monitor stations.

S.No.	Name of Neutron Monitor station	Time interval	Latitude	Longitude	Altitude(m)	Cut of rigidity in (GV)
1	Moscow	1965-14	55.4N	37.3E	200	2.39
2	Kiel	1965-08	54.3N	10.1E	54	2.36

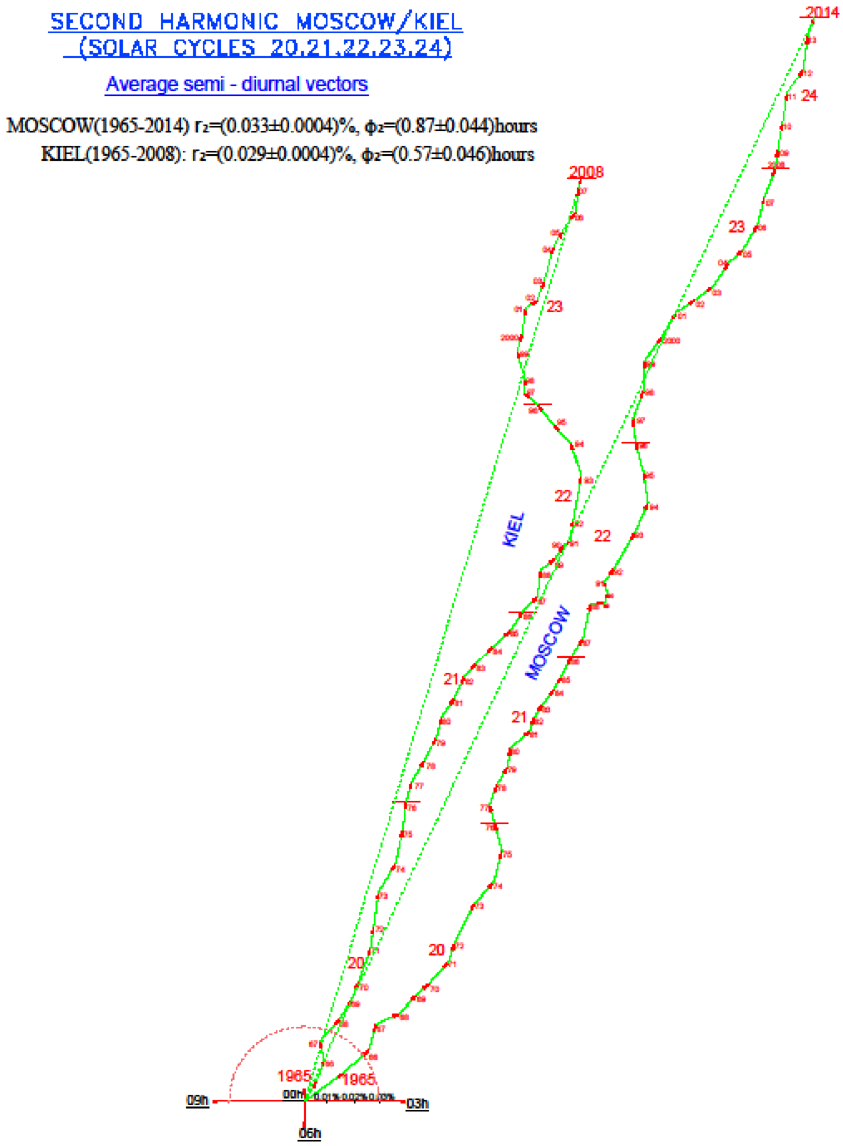

Figure 1 The Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays of Moscow neutron monitor station for the years 1965-2014 and Kiel neutron monitor station for the years 1965-2008 . The overall average values are also marked.

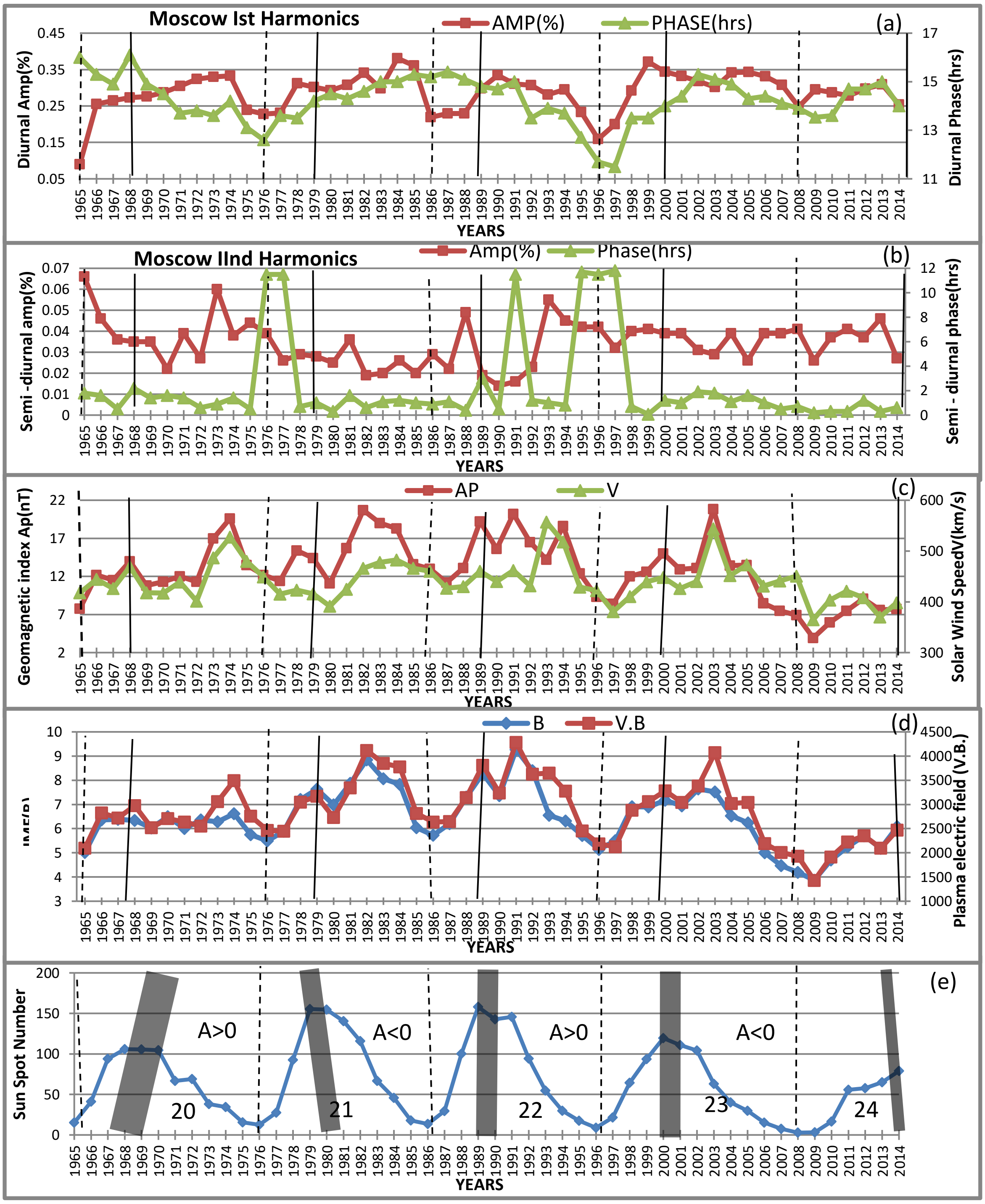

Figure 2: Shows the yearly averages of (a) Diurnal vectors (amp. and phase for moscow NM) (b) Semi-diurnal vectors (amp. and phase for Moscow NM) (c) Geo-magnetic index (Ap) and solar wind speed(V) (d) IMF(B) and Plasma electric field (V.B.) (e) Sunspots number for each year from 1965 to 2014 (solar cycle 20 to 24).

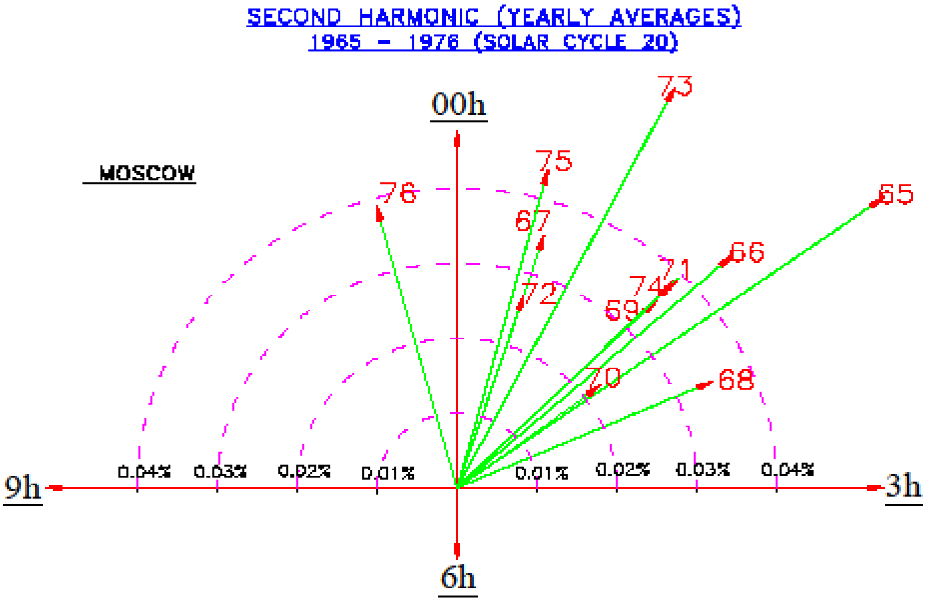

Figure 3 : Shows the harmonic dial representation of annual average vectors of the second harmonics of the observed daily variation of cosmic ray for Moscow neutron monitor station for the years 1965-1976(solar cycle 20).

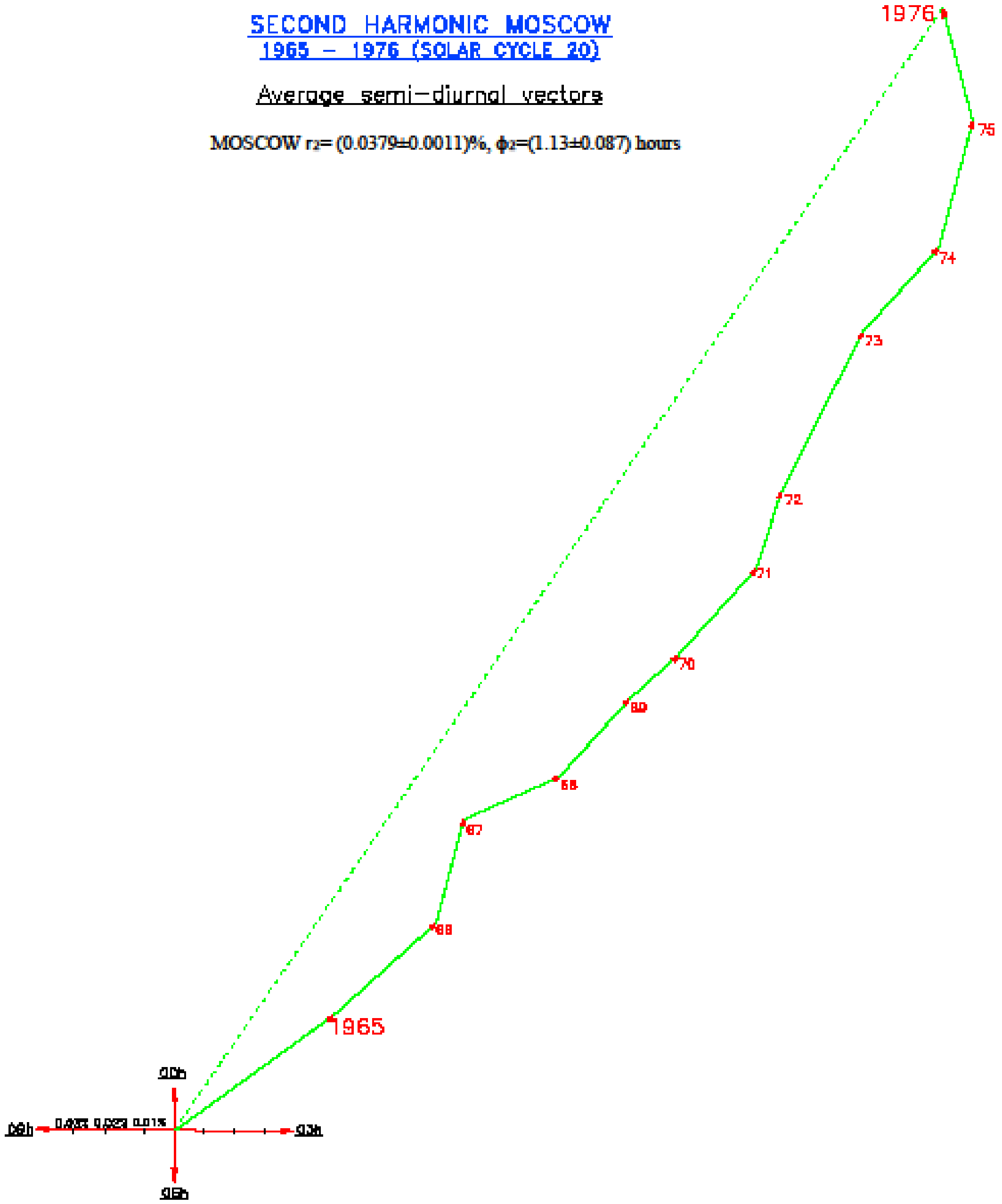

Figure4 : Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays for Moscow neutron monitor station for 1965-1976 (solar cycle 20). The overall average values are also marked.

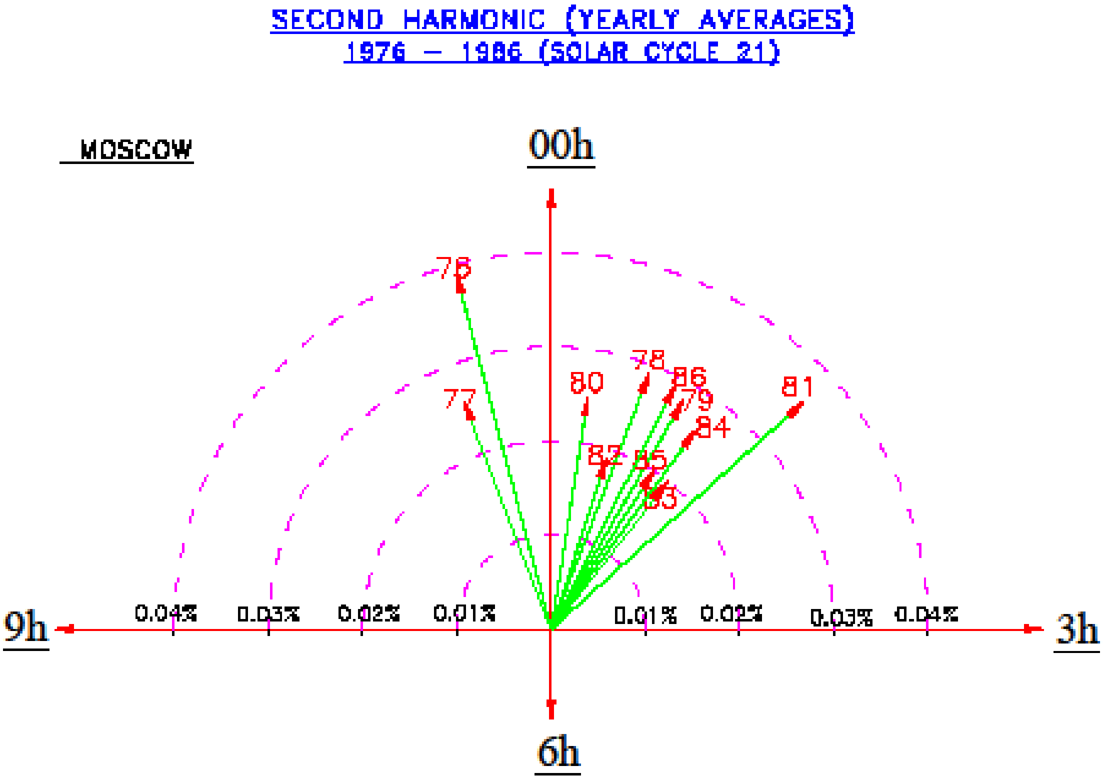

Figure5: Shows the harmonic dial representation of annual average vectors of the second harmonics of the observed daily variation of cosmic ray for Moscow neutron monitor station for the years 1976-1986(solar cycle 21).

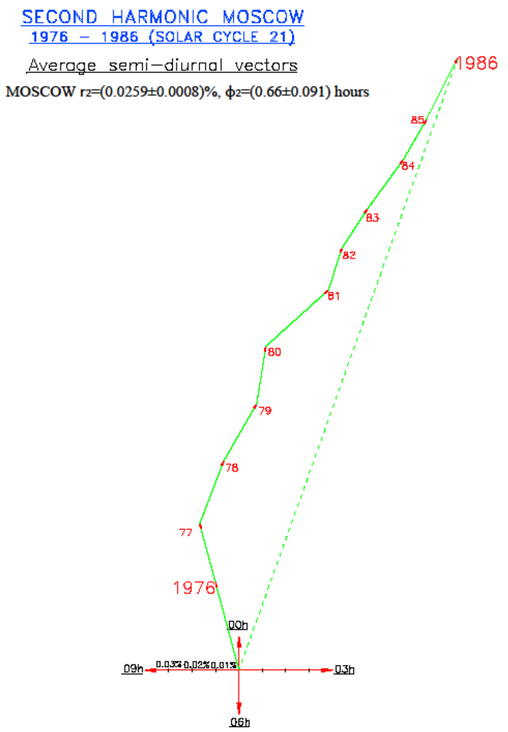

Figure6: Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays for Moscow neutron monitor station for 1976-1986 (solar cycle 21). The overall average values are also marked.

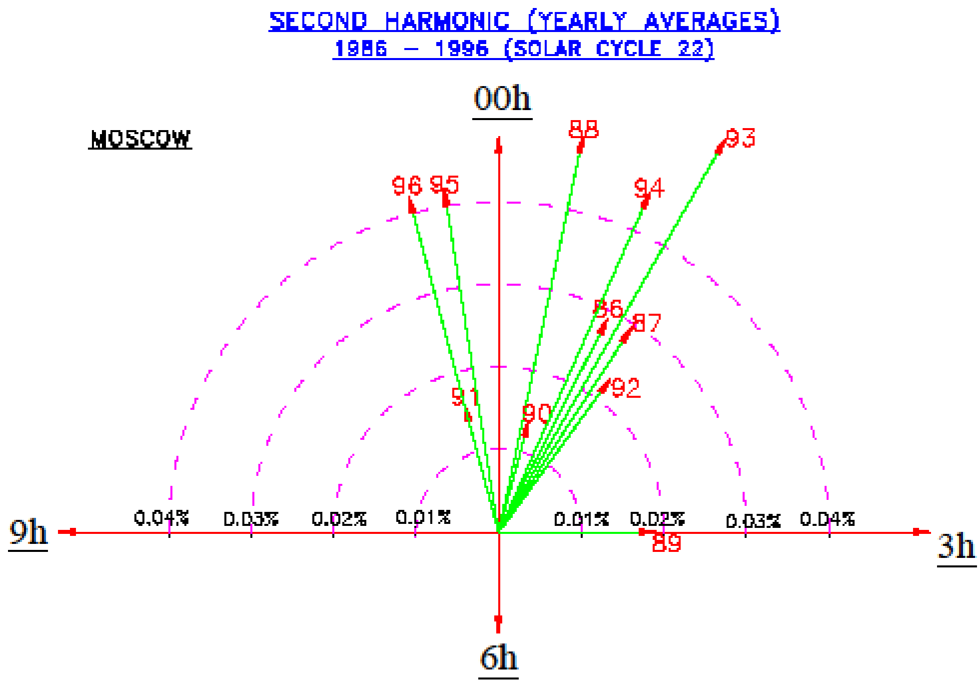

Figure7: Shows the harmonic dial representation of annual average vectors of the second harmonics of the observed daily variation of cosmic ray for Moscow neutron monitor station for the years 1986-1996(solar cycle 22).

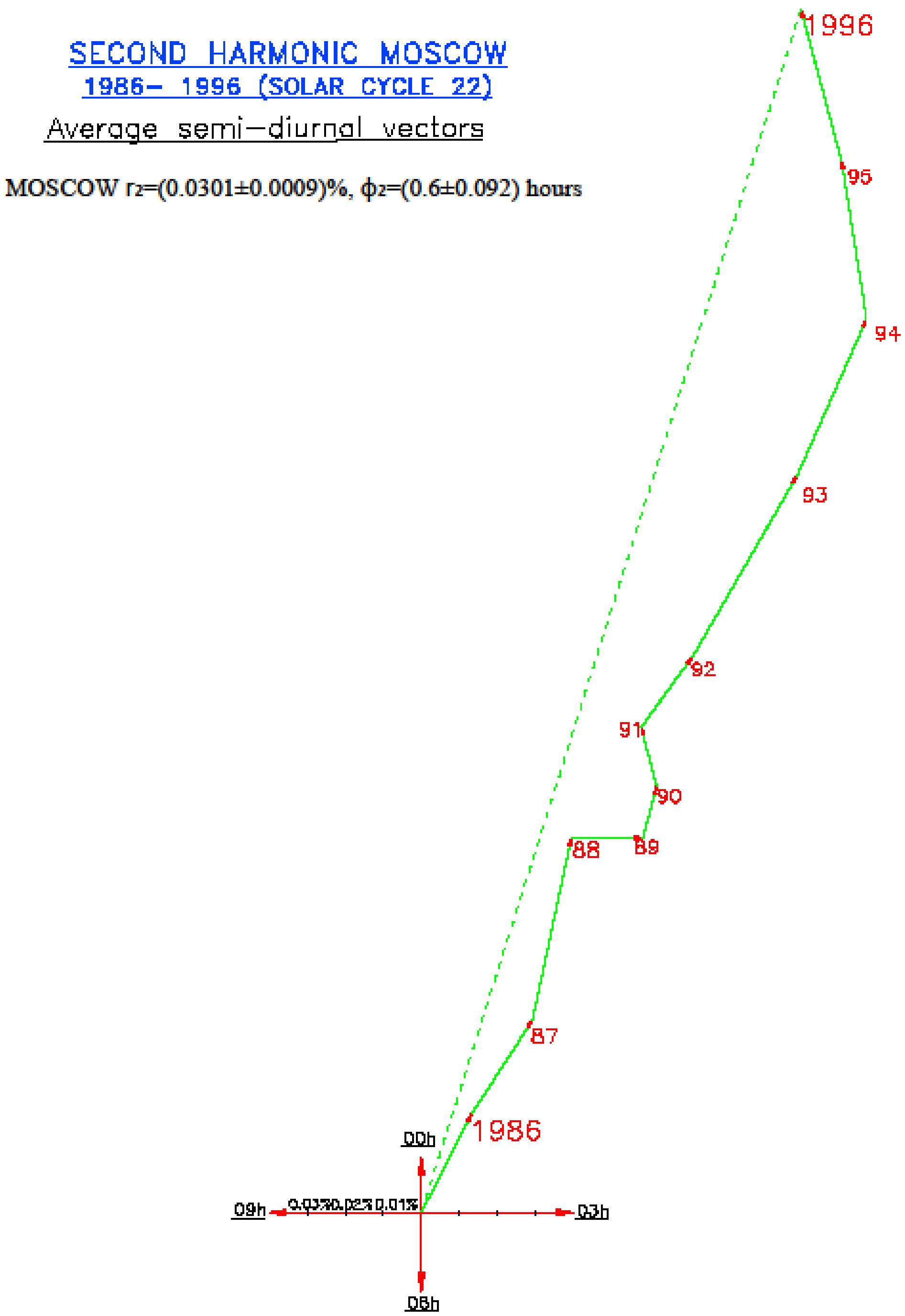

Figure8: Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays for Moscow neutron monitor station for 1986-1996(solar cycle 22). The overall average values are also marked.

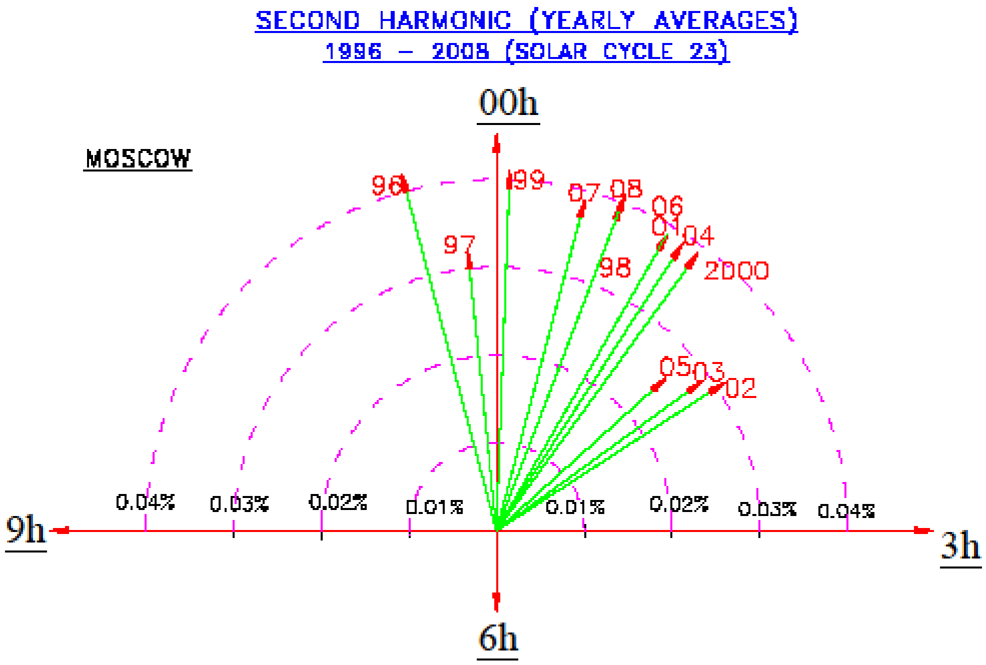

Figure9: Shows the harmonic dial representation of annual average vectors of the second harmonics of the observed daily variation of cosmic ray for Moscow neutron monitor station for the years 1996-2008(solar cycle 23).

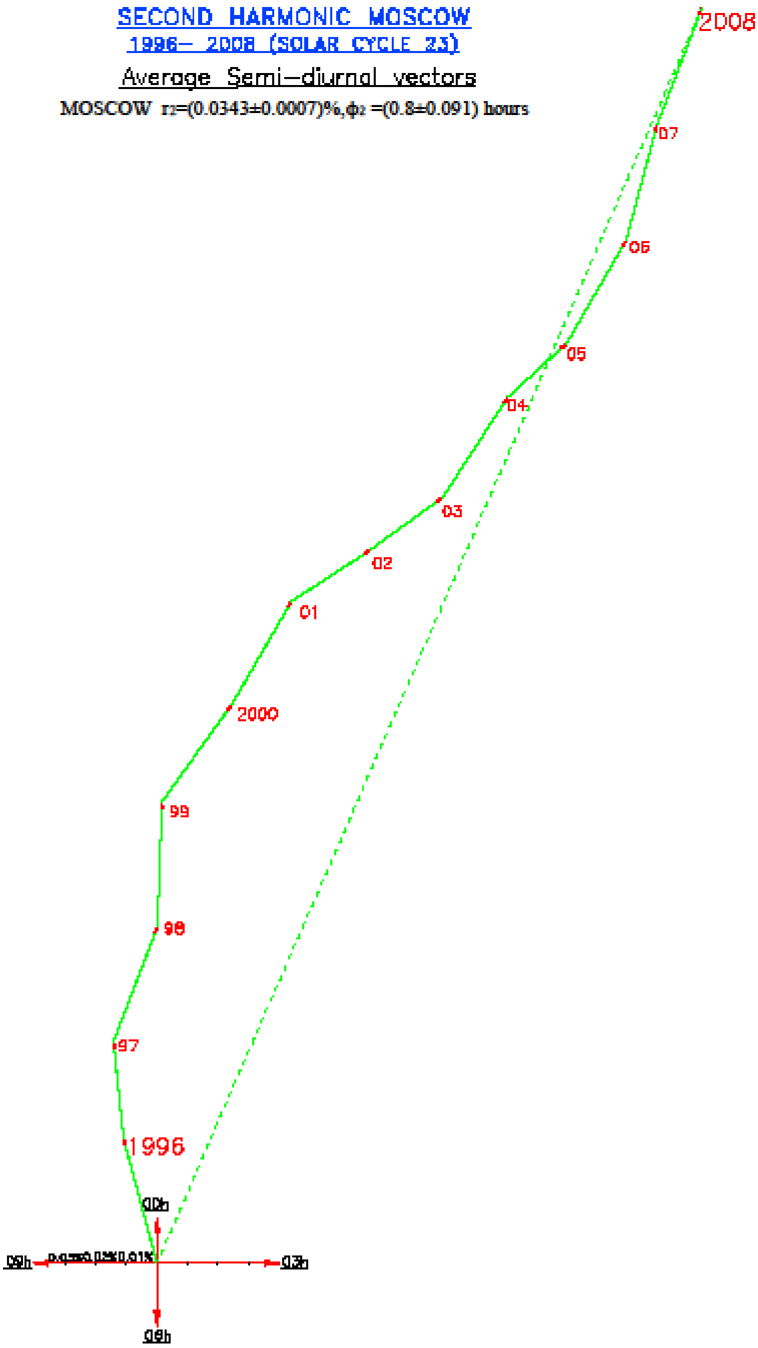

Figure10: Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays for Moscow neutron monitor station for 1996-2008 (solar cycle 23). The overall average values are also marked.

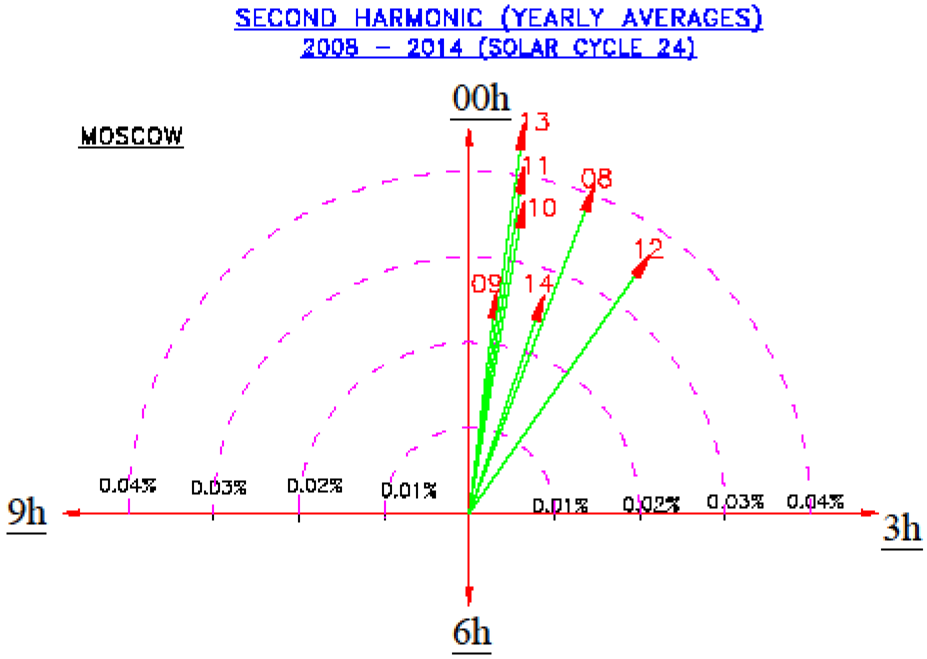

Figure11: Shows the harmonic dial representation of annual average vectors of the second harmonics of the observed daily variation of cosmic ray for Moscow neutron monitor station for the years 2008-2014(solar cycle 24).

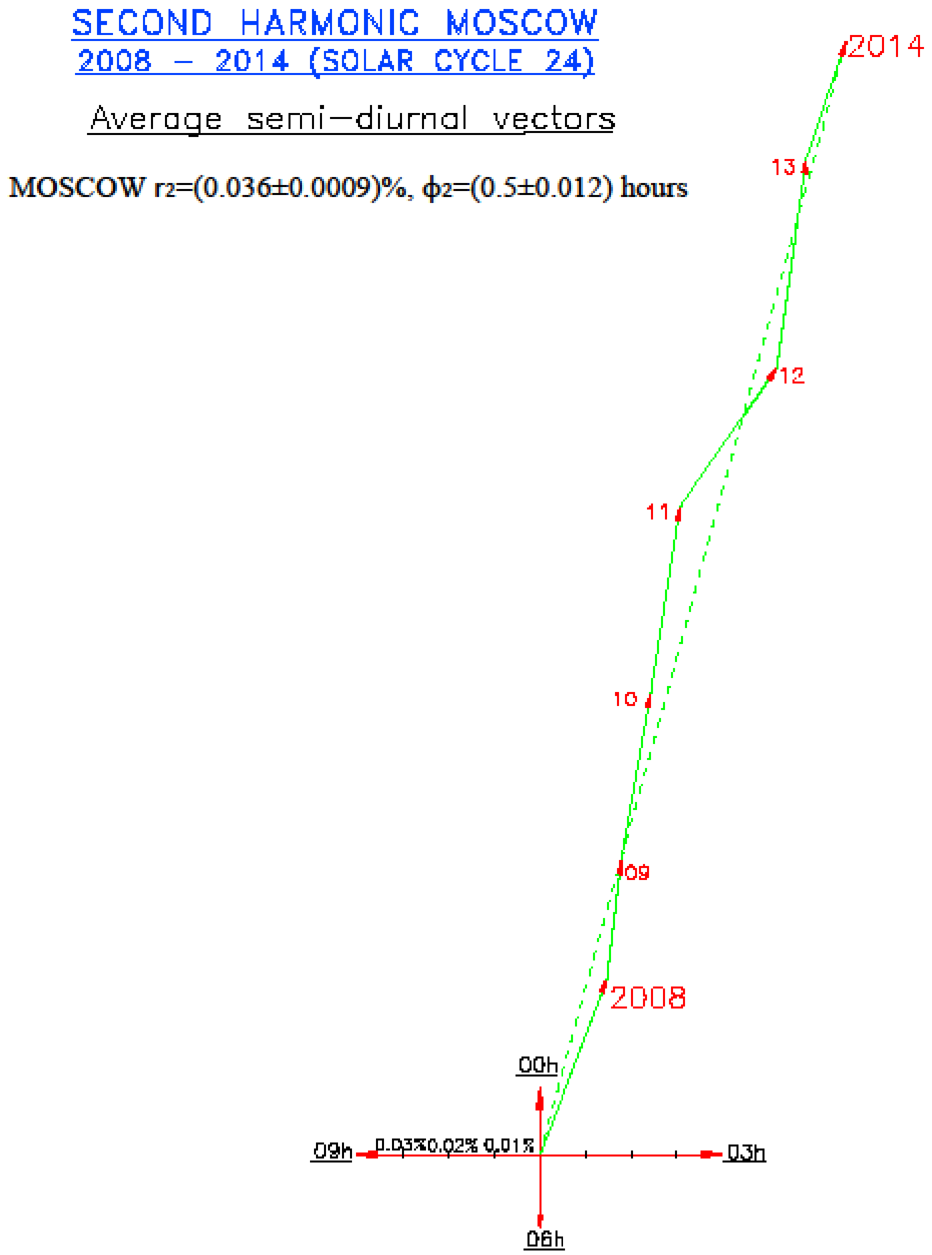

Figure12: Vector-addition diagram of the annual –average vectors of the second harmonic of the observed daily variation of cosmic rays for Moscow neutron monitor station for 2008-2014 (solar cycle 24). The overall average values are also marked.

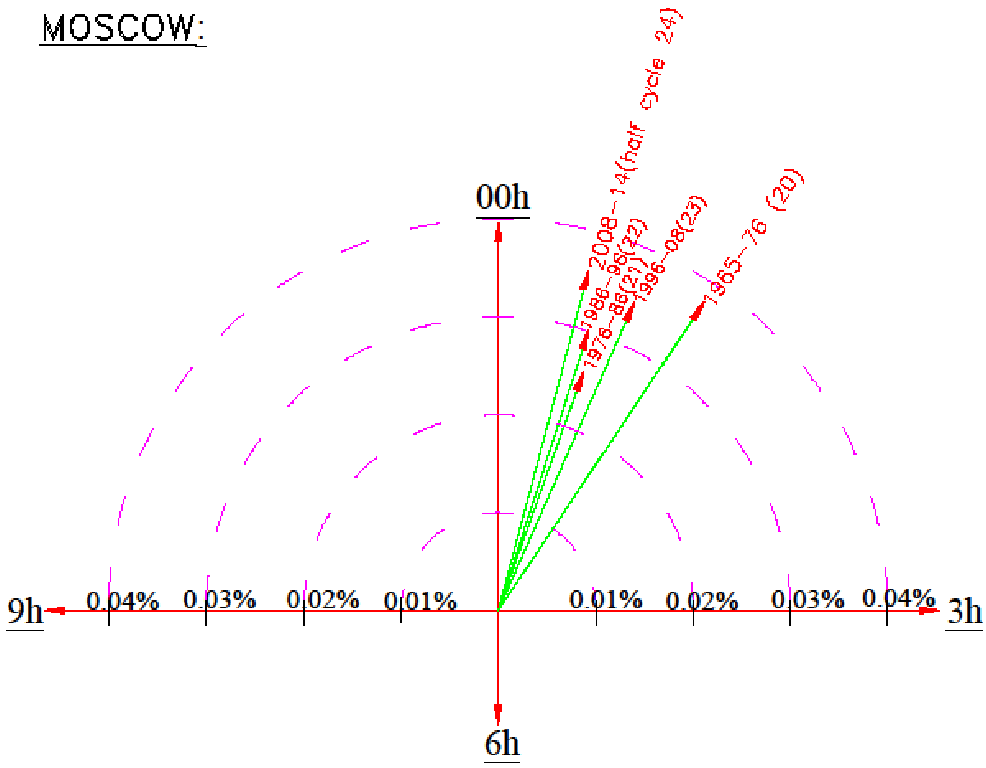

Figure13: Harmonic dial representation of the observed semi-diurnal vectors averaged over complete solar cycles 20,21,22,23 and ascending phase of 24 for Moscow neutron monitor stations.

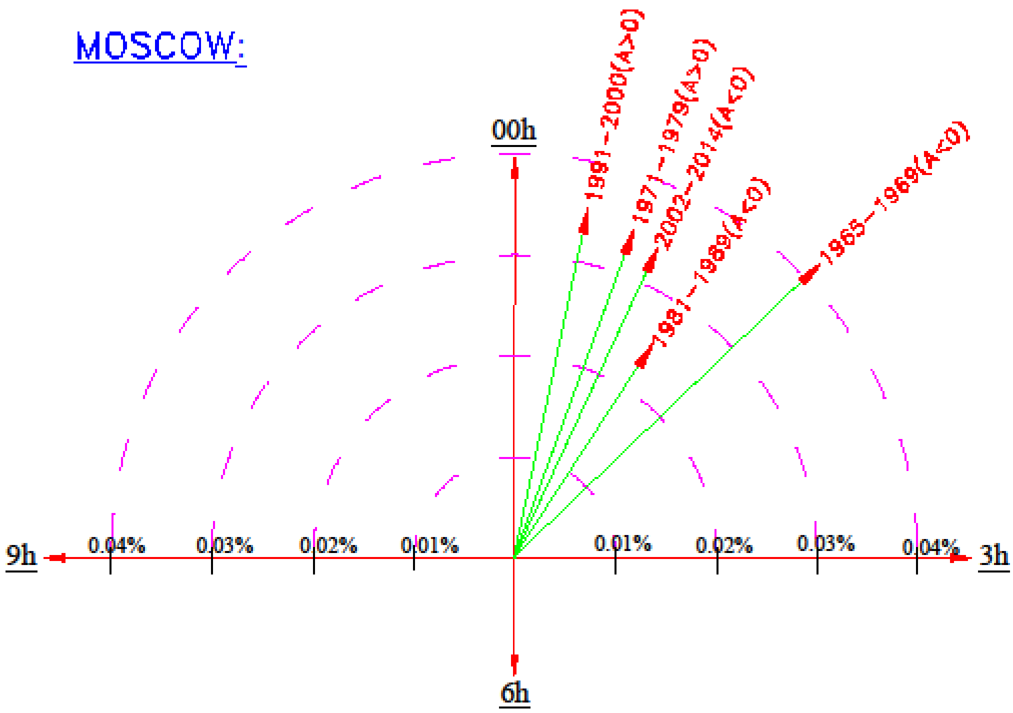

Figure14: Harmonic dial representation of the observed semi-diurnal vectors averaged over positive polarity state (A>0) and negative polarity state (A<0) solar cycles 20,21,22,23 and 24 for Moscow neutron monitor stations.