Solar Rotational Oscillation and Its Subharmonics in Solar Wind Plasma Field, Geomagnetic, and Cosmic Ray Intensity Indicator in the Solar Cycle 24/25 Minimum

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Abstract To study synodic period and its subharmonics, we have utilized hourly average data of solar wind plasma field, geomagnetic index, and galactic cosmic ray intensity along with 5 min average data of selected solar wind field parameters during the recent minimum of Solar Cycle 24. Wavelet analyses of hourly average data reveal 28.1, 13.1, and 6.8 day of sigma in interplanetary magnetic field; 27.1, 13.1, and 9.0 day of plasma speed; 27.1, 13.6, 3.9, and 2.2 day of interplanetary electric field; 27.1, 13.6, 3.8, and 2.2 day of southward component of magnetic field; 26.2, 13.6, 8.6, and 3.0 day of geomagnetic Ap index; and 28.1, 11.0, 9.3, 7.0, and 1.6 day periods of galactic cosmic ray intensity. In addition to these prominent short-term periods, we have significantly observed 6.6, 3.3, and 1.7 day periods of sigma in interplanetary magnetic field ($\sigma_B$); 5.6, 4.2, and 2.2 day of electric field ($E_y$) and 5.6, 3.3, and 2.4 day of southward component of magnetic field ($B_z$) in the 5 min average data. During the recent solar minimum, we have observed one solar rotational period and its second, third, fourth, fifth, sixth, seventh, eighth, tenth, eleventh, and twelfth subharmonics. The observed subharmonics of solar rotational period make the current solar minimum very special and noteworthy to study.

1. Introduction

Various solar wind plasma and field parameters, geomagnetic indices, and cosmic rays are good indicators to measure solar activity. Interplanetary magnetic field (IMF) is one of them, which is generated deep inside the Sun by the dynamo process (Parker, 1955). This magnetic field is transported from the convection zone to outer layers; part of it escapes from the Sun and spreads out in the outer space called IMF. Variation in IMF and other solar wind plasma and field parameters help us to understand the Sun. Fundamental periods are easily observed in solar wind plasma, geomagnetic activity indices, and cosmic ray intensity indicators, but it requires rigorous study to bring higher subharmonics into light. Lots of short-term periods have been reported by scientists and researchers since long back. The 27 day period of the Sun was observed in cosmic ray intensity and reported in 1938 (Forbush, 1938), its second subharmonic (13.5 day) in 1996 (Mursula & Zieger, 1996) and third harmonic (9.0 day) in 2011 (Sabbah & Kudela, 2011). Recently, Singh and Badruddin (2019a) reported fourth (6.8 day), fifth (5.5 days), and sixth (4.6 day) subharmonics of synodic period in various solar wind plasma and field parameters during solar polarity reversal periods of solar cycles and during solar minimum periods (Singh & Badruddin, 2015a).

Short-term periods like 20, 26, 29, 30, 32, and 34 day of $B_z$ were reported by Chowdhury et al. (2015) during 2009 to August 2014; 13.9, 28, and 30 day periods of $B_z$ by Katsavrias et al. (2012) during 1964–2010; 1.9, 3.3, 4.2, 8.8, 9.5, 13.4, 13.8, 27.5, and 28.3 day periods by Singh and Badruddin (2015a, 2015b) during solar minimum; 29 day by Gavryuseva (2018) in 2003; 13.9, 14.3, 27.8; and 28.5 day periods by Tsichla et al. (2019) during 1995–2018. Recently, 3.9, 2.8, 2.4, 2.2, and 1.8 day periods of various solar wind plasma and field parameters have been reported by Singh and Badruddin (2019a) during the polarity reversal periods and 1.7, 1.8, 2.2, 3.3, and 3.8 day periods during solar minimum (Singh & Badruddin, 2015a, 2015b). Short-term variations like 1.7, 2.4, 2.8, 3.3, and 3.8 day periods are also significantly reported in $B_z$, $E_y$, and $AE$ index using high-resolution data (Singh & Badruddin, 2019b) during different periods including solar minimum and solar polarity reversals. Earlier, Gonzalez and Gonzalez (1987) found significant peaks of 27.5, 13.5, 9.1, and 6.8 day periods in IMF and Bower (1992) reported 12–14 and 26–28 days periodicities in...
solar irradiance and solar activity indices. Prabhakaran Nayer et al. (2002) found 27 and 14 day periodicities in various solar wind plasma and field parameters and 27.8 day period in $AE$, $\beta$, and $Kp$ indices; 13.9 and 27.8 day periods in $Ap$, $D_{st}$, plasma speed, temperature, density, and $x$, $y$, and $z$ components of IMF were reported by Katsavrias et al. (2012).

Many techniques (like power spectral analysis and wavelet analysis) have been used to study the periodic and nonperiodic behaviors of solar wind plasma and field parameters, geomagnetic indices, and cosmic rays intensity time series. A number of periods have been reported; some linkage has been established among many of them (Bai & Sturrock, 1991; Chowdhury et al., 2019; Krivova & Solanki, 2002; Mursula & Zieger, 1996; Sabbah & Kudela, 2011; Singh & Badruddin, 2019a). The origin of solar rotational period and its harmonics in IMF were discussed by Choi and Lee (2019). The aim of this work is to study one solar rotational period and its subharmonics during the current solar minimum using hourly and 5 min averaged time series of plasma speed, sigma in IMF, electric field, southward component of IMF, geomagnetic activity $Ap$ index, and cosmic rays intensity (Oulu NM). For this purpose, we have utilized wavelet analysis technique to look for one solar rotation period and its subharmonic during the August 2017 to June 2019 (minimum between Solar Cycles 24/25) along with 5 min average data of sigma in IMF, electric field, and southward component of magnetic field during 11 February 2019 to 12 May 2019. Through this study, we have found noteworthy results of the recent solar minimum between Solar Cycles 24/25, which makes current solar minimum interesting to study for research purposes. Wavelet analyses of hourly average time series reveal synodic period and second subharmonic and fourth subharmonic of sigma in IMF ($\sigma_B$); synodic period and second subharmonic and third subharmonic of plasma speed ($V$); synodic period and second subharmonic, seventh subharmonic, and twelfth subharmonic of interplanetary electric field ($Ey$); synodic period and second subharmonic, seventh subharmonic, and twelfth subharmonic of southward component of magnetic field ($Bz$); and synodic period and second (11.0 day, shift toward narrower side), third, fourth (7.0 day, extended), and 1.6 day periods of galactic cosmic ray intensity. It sounds good to obtain simultaneous and significant presence of higher subharmonics of solar rotational period in the high-resolution (5 min average) data of $\sigma_B$, $Ey$, and $Bz$. In this work, we have significantly observed 6.6 (fourth subharmonic), 3.3 (eighth subharmonic), and 1.7 day periods of $\sigma_B$; 5.6 (fifth subharmonic), 4.2 (sixth subharmonic), and 2.2 day (twelfth subharmonic) of $Ey$; and 5.6 (fifth subharmonic), 3.3 (eighth subharmonic), and 2.4 day (eleventh subharmonic) of $Bz$ in the $Ey$ and $Bz$ time series. Appearance of such good range of significant subharmonics of solar rotational period (26.4 day) makes current minimum very special and noteworthy to study.

### 2. Data and Analysis Technique

In this study, we have utilized hourly average data of selected solar wind and interplanetary parameters (solar wind velocity, sigma in IMF, electric field, and southward component of magnetic field), a geomagnetic activity parameter ($Ap$ index), and a cosmic ray intensity (Oulu neutron monitor count rate), in addition to high-resolution (5 min average) data of sigma in IMF, electric field, and southward component of magnetic field time series. For this work, we have selected hourly data during 1 August 2017 to 30 June 2019, the region with the least number of sunspot numbers of the current solar minimum of the solar cycles between 24/25. The high-resolution time series data are selected from 11 February 2019 to 12 May 2019 period. The low-resolution data of solar wind plasma and field parameters and geomagnetic index were obtained from the National Space Science Data Center, OMNI database (https://omniweb.gsfc.nasa.gov/form/dx1.html), and high-resolution data are available online (https://omniweb.gsfc.nasa.gov/form/omni_min.html). The hourly cosmic rays data were selected from http://www.cosmicrays.oulu.fi/ website. Both low- and high-resolution data of all the considered parameters were then subject to wavelet analysis. We used Morlet wavelet (Torrence & Compo, 1998) to study the solar rotational period and its subharmonics. Results were obtained using a single selected mother function (Morlet) and scaling parameters.

It is difficult to detect small short-term variations because of their low amplitudes using low-resolution (hourly average and so) data; hence, we have used high-resolution (5 min average) data of selected parameters during the period of solar minimum of the current solar cycle. The high-resolution data set has more than 26,000 data points of each of the time series, and the chosen period has very little data gaps as well. We
filled these data gaps with zeros so the program knew that there is no value. This will appear as blank in our power spectrum and will not affect the periodicities that we are detecting.

In the wavelet analysis method, wavelet power spectrum (WPS) and global wavelet spectrum (GWS) provide the exact temporal and spatial variations of the nonrecurrent and recurrent signals of the time series. Any time series is expanded in terms of time-localized wavelets and its two-dimensional representation (see Morlet et al., 1982; Torrence & Compo, 1998) is

\[ f(t, t', n) = \exp(2i\pi nt) \cdot \exp\left(-n^2 \frac{(t-t')^2}{2}\right) \]

where \( n \) is the frequency and \( t' \) the delay time.

The time-averaged wavelet spectrum over all the local wavelet spectra (i.e., the GWS) is given by

\[ W^2(x) = \frac{1}{N} \sum_{n=0}^{N-1} |W_n(x)|^2 \]

where \( W_n(x) \) is the wavelet power and \( N \) the number of local wavelet spectra.

In this work each wavelet power is obtained by using Morlet wavelet assuming the existence of a red-noise power spectrum with dimensionless frequency \( \omega_o = 8 \) (Torrence & Compo, 1998), which gives reasonable spectral and temporal resolution.

The WPS provides information as regards the levels of the spectral power corresponding to each variation at different time periods. The yellow and green (light) areas correspond to the lower-power regions, and the red areas correspond to the regions with higher power. The colored (light) red regions, however, in all of the figures indicate the region of the spectrum below the 95% confidence level, and the thick contours (dark red regions in the black contour) are the regions of the spectrum at 95% confidence level. In the global power spectrum (right panel) of each wavelet figure, the variation in power is shown with a period and the thick dashed line in the panel represents the 95% confidence level. The cone of influence is also shown in all the wavelet power spectra, as it describes the region influenced by the zero padding or shows edge effects (Singh & Badruddin, 2015b).

### 3. Results and Discussion

In Figure 1 daily averaged values of the southward component of IMF \((B_z, \text{nT})\), the sigma in IMF \((\sigma_B)\), the solar wind plasma speed \((V, \text{km s}^{-1})\), the electric field \((E_y)\), the geomagnetic activity index \((Ap, \text{nT})\), and cosmic ray intensity (counts per minute) for the recent solar minimum (1 August 2017 to 30 June 2019) are plotted. This figure shows the time variations in these parameters, in which the cosmic ray intensity counts are maximum in general, while the fluctuations of geomagnetic activity parameter \(Ap\) index and sigma in IMF are small during the minimum period. The amplitude of fluctuations of southward component of magnetic field and electric field time series are also small during the period. Since coronal holes region become dominant during the solar minimum periods hence solar wind plasma speed are comparatively higher during the minimum period, which is probably due to the occurrence of high-speed solar wind streams.

Solar rotational period and its subharmonics of hourly averaged sigma in IMF, plasma speed, and electric field time series are shown in Figure 2. The upper panel of the figure shows the WPS and GWS of the hourly values of sigma in IMF \((\sigma_B)\). The fourth subharmonic of synodic period (6.8 day) of the time series is much strong during the minimum period; however, its second subharmonic (13.1 day) is active during the beginning and at the end of the minimum. Fundamental period (~28.1 day) of the series has steep peak as shown in the GWS, which is comparatively strong during the mid of 2018 and early 2019. The middle panel of the figure is WPS and GWS of the hourly averaged time series of solar wind plasma speed. The three significant periods are observed in the GWS of the plasma speed time series. The synodic period (27.1 day) is dominant during the whole minimum period and which has maximum peak amplitude as shown in the spectrum. The second subharmonic of synodic period (13.1 day) is also significantly observed during the minimum, while
its third subharmonic (8.9 day) has broad peak. The lower panel of the figure is WPS and GWS of the hourly averaged electric field time series. The two significant variations are observed in the GWS of the panel, which has steep peaks as appearing in the WPS of the figure. The amplitude of fundamental period (27.1 day) is about one and half times more than the amplitude of second subharmonic (13.6 day) period. The synodic period is strong during the early 2018, 2019, and late 2017; however, its second harmonic is prominent during late 2017 and early 2019. In addition to these two prominent periods, signatures of two more periods (3.9 and 2.2 days) are also observed in the WPS and GWS of the electric field time series. All these variations along with their power are tabulated in Table 1.

Figure 3 depicts the GPS and GWS of hourly resolution data of southward component of IMF (upper panel), geomagnetic parameter Ap index (middle panel), and cosmic ray intensity (lower panel). The synodic period (27.1 day) of Bz time series is very prominent and strong during early 2018 and 2019, which appears strong in the WPS of the figure (upper panel). The 13.6 day (second subharmonic) period is also significant and has almost half of peak amplitude than its succeeded periods. This subharmonic is strong during the late 2017. The signatures of two insignificant variations (3.8 and 2.2 day, which could be the higher subharmonics) are also observed in the time series as shown in the upper panel of the figure. The observed periods with their power are tabulated in Tables 1 and 2. The four significant short-term periods that correspond to Ap index are observed in the middle panel of GWS of the figure. The solar rotational period (26.2 day) is strong during the minimum period as shown in the WPS of the panel. The 13.1 day period has feeble contours in the WPS in the figure compared to 26.2 day variation. However, this subharmonic (13.6 day) has more peak power value than its fundamental period also has very steep peak during the period. The third short-term period (8.6 day) is strong as well as significant during the late 2017, around the middle of 2018, and early 2019 and has broad peak. The significant signature (in WPS) and peak (in GWS) of ninth subharmonic (3.0 day) also appears in the middle panel of the figure, this period is strong during late 2017 and late 2018. The wavelet analysis of hourly values of cosmic rays counts (Oulu NM) are shown in the lower panel of the figure. The fundamental period (28.1 day) is only the prominent period of cosmic rays intensity; however, feeble signatures of four other short-term periods (11.0, 9.3, 7.0, and 1.6 day) also appeared in the WPS and GWS of the cosmic ray intensity time series. The power variation corresponding to 28.2 day period is very narrow and has intense peak moreover the contours corresponding to this variation appeared during the whole minimum period.

To search for and confirm the higher subharmonics of synodic period, we have utilized high-resolution (5 min averaged) data of Ap index in IMF (sigma in B), electric field and southward component of magnetic field for our study. The WPS and GWS of high-resolution time series are shown in Figure 4. The upper panel of the figure shows WPS and GWS of the sigma in IMF time series. The three significant variations (6.6, 3.3, and 1.7 day) are observed in the WPS of the time series (upper panel). The 6.6 day period is strong and observed during the whole examined period. The peak of this period is very steep; however, the peak corresponding to 3.3 day (eighth subharmonic) period is broad one and observed during the whole examined period. The third variation (1.7 day) of the time series is significantly observed in WPS and GWS of the panel also. This variation could be the higher subharmonic of the fundamental period. The middle panel of the figure shows WPS and GWS of the high-resolution electric field time series. The fifth subharmonic (5.6 day) has low amplitude among other observed variations; however, the period is significant and strong during the whole data length. The sixth harmonic (4.2 day) is also significant period of the time series and observed strongly during the examined period. The third short term variation (2.2 day, could be the twelfth subharmonic) is also significant and has steep peak in the high-resolution time series, this variation has comparable

Figure 1. Daily averaged plot of southward component of interplanetary magnetic field (Bz, nT), sigma in IMF (σB), solar wind plasma speed (V, km s−1), electric field (Ey, nT), geomagnetic index (Ap, nT), and cosmic ray intensity (CRI, counts per minute) time series during Solar Cycle Minimum 24/25 (1 August 2017 to 30 June 2019).
amplitude with the other observed periods. The lower panel of the figure shows WPS and GWS of the high-resolution time series of southward component of the magnetic field. Three significant variations (5.6, 3.3, and 2.4 day) are observed in the time series. The 5.6 and 3.3 day variations are strong during the whole examined period and these could be the fifth and eighth subharmonics of fundamental period. The dashed line in the GWS represents the 95% significant level. The color bar of the figure is also shown.

**Table 1**

| Period (d) | Power | Period (× 10^5) | σB | V | Ap | Ey | Bz | Oulu NM |
|------------|-------|----------------|----|---|----|----|----|--------|
| 6.8 | 39.8 | 8.9 days | 4.5 | 3.6 | 2.2 days | 0.669 | 7.0 days | 0.024 |
| 13.1 | 29.0 | 13.6 days | 6.6 | 12.6 | 3.9 days | 2.008 | 9.3 days | 0.396 |
| 28.1 | 31.6 | 27.1 days | 9.8 | 18.9 | 3.8 days | 2.986 | 11.0 days | 0.415 |
|         |       |               |    |    | 27.1 days | 13.6 days | 27.1 days | 0.415 |
|         |       |               |    |    | 27.1 days | 27.1 days | 113.3 | 28.1 days |

**Figure 2.** Wavelet power (WPS) and global wavelet (GWS) spectrum of hourly average time series of sigma in interplanetary magnetic field (upper panel), plasma speed (middle panel), and electric field (lower panel) during the 1 August 2017 to 30 June 2019 (solar minimum). The cone of influence is also shown in each WPS.
2.4 period (could be eleventh subharmonic) has also good signatures in the WPS of the time series which has comparable amplitude with the other two variations.

Gonzalez and Gonzalez (1987) found that amplitude of 27.5, 13.5, 9.1, and 6.8 days periods are in the same order of periods. But there is no such definite pattern observed between amplitude and its period. Singh et al. (2012) have shown that amplitude of synodic period and its second and third harmonics have not any such relation. Recently, Singh and Badruddin (2019a) reported enhance amplitude of 4.6 day period of IMF and plasma speed compared to its parent period and its other higher subharmonics during polarity reversal period of Solar Cycle 20, but such pattern was not observed in other parameters. However, comparable amplitude of synodic period and its subharmonics were reported during the reversal period of Solar Cycle 21. During the reversal period of Solar Cycle 22, authors found that the 12.7 day period was only the intense period of IMF and plasma speed, but in the case of Ap index dominant peak corresponding to extended synodic period (35.8 day) was observed and broad peaks of other subharmonics were observed. While in the case of cosmic rays intensity, mixed amplitudes of subharmonics (2.3, 4.6, 6.8,
12.7, 19.2, and 35.8 day) were observed. Reversal period of Solar Cycle 23 has some mixed amplitude subharmonics observed in IMF, plasma speed, and \( A_p \) index time series similar to the reversal period of previous odd cycle (Solar Cycle 22), while a single intense peak of synodic period was reported in cosmic rays intensity during the reversal period of Cycle 23. In the case of reversal period of Solar Cycle 24, fourth subharmonic (6.8 day) of synodic period is much intense among all the other periods; however, in the case of plasma speed amplitude of synodic period (28.1 day) is much higher than its second and third subharmonics. In the case of \( A_p \) index again mixed amplitude short-term periods were reported. From these studies, it can be inferred that the amplitude of subharmonic does not have any definite relationship with its period.

During the minimum between Solar Cycles 23/24, the amplitude of third subharmonic of synodic period is much enhanced followed by second harmonic. However, the amplitude of fundamental period (i.e., synodic period) is comparable with the sixth subharmonic of IMF time series; similar pattern of amplitudes was reported in sigma in magnetic field. In the case of plasma speed the presence of significant peaks at about 26.8, 13.6, and 9.1 days was observed during the same minimum with amplitudes decreasing in that same order. In the case of southward component of magnetic field and electric field time series, synodic period, second harmonic, third harmonic (only in \( E_y \) time series), extended fourth harmonic (7.1 day, in the case

Figure 4. Wavelet power (WPS) and global wavelet (GWS) spectrum of 5 min average time series of sigma in interplanetary magnetic field (upper panel), electric field (middle panel), and southward component of magnetic field (lower panel) during the period 11 February to 12 May 2019. The cone of influence is also shown in each WPS. The dashed line in the GWS represents the 95% significant level. The color bar of the figure is also shown.
of $B_z$, fourth harmonic, and prominent 1.7 day (in $B_z$ time series) and 1.9 day (in $E_y$ time series) are reported. In these field parameters amplitude are in that same order of periodicities. The comparable amplitudes of fundamental period and its subharmonics were reported in $AE$ index, while amplitude of 1.7 day period was much lower. During the minimum between Solar Cycle 22/23, the amplitude of fundamental period and its subharmonics are in that same order of IMF, plasma speed, cosmic ray intensity, $D_{st}$, and $AE$ index. While in the case of sigma in IMF time series, nearly same amplitude of fundamental period and its subharmonics were reported, and in the case of $B_z$ and $E_y$ time series, amplitude of second subharmonic (13.4 day) was much enhanced and reported amplitude of other short-term periods was nearly equal (Singh & Badruddin, 2015a). Previous studies also suggest that amplitude of one solar rotational period and its subharmonics of cosmic ray intensity decreases as in the period of solar polarity reversal (Singh & Badruddin, 2019a) and during solar minimum (Singh & Badruddin, 2015a, 2015b) of solar cycles; however, polarity reversal period of Solar Cycle 20 was exception in this study, where amplitude of second subharmonic (13.1 day) was a bit greater than that of its fundamental period (27.0 day).

4. Conclusion

Besides synodic period and its second ($\approx$13.5 day), third ($\approx$9.0 day), fourth ($\approx$6.8 day), fifth ($\approx$5.5 day), and sixth ($\approx$4.4 day) subharmonics, the amplitude $3.9, 3.3, 3.0, 2.4, and 2.2$ day periods are strong and significant during the minimum; hence, these periods could be seventh, eighth, ninth, eleventh, and twelfth subharmonics of synodic periods respectively, as reported in Singh and Badruddin (2019b). Some temporal shift may be their source regions because behavior of the dynamo process of the Sun behaves differently in solar cycles (Dikpati, 2013) and dynamic variations of convection zone by Howe et al. (2000). Unpredictable behavior of amplitude of periods with the synodic period and its subharmonics may be due to the relative activity of source regions (Singh & Badruddin, 2019b). The southward component of magnetic field, electric field, geomagnetic $Ap$ index, and cosmic ray intensity are good indicators as signatures of higher subharmonics are observed in the hourly average of these time series. However, higher subharmonics are significantly observed in all the considered parameters. Many of the results obtained in this study have good agreement with the results obtained by Singh and Badruddin (2015a, 2019a and 2019b) during the solar minimum and solar polarity reversal periods of the solar cycles.

Good signatures of ninth subharmonic (3.0 day) in the geomagnetic $Ap$ index and twelfth subharmonic (2.2 day) in the interplanetary electric field ($E_y$) and southward component of IMF ($B_z$) are observed in the low-resolution time series. These results are well supported when high-resolution data (5 min averaged) are subjected to wavelet analysis. In addition to these higher subharmonics, the dominant fourth harmonic (6.8 day) of sigma in IMF and only significant one rotational period (28.1 day) of cosmic ray intensity in low-resolution time series makes the current solar minimum special and noteworthy to study.

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