North–South Asymmetry in Rieger-type Periodicity during Solar Cycles 19–23

Eka Gugnashvili1, Teimuraz V. Zaqarashvili1,2,3, Vasil Kukhianidze1, Ramon Oliver4,5, Jose Luis Ballester4,5, Mausumi Dikpati6, and Scott W. McIntosh6

1 Abastumani Astrophysical Observatory at Ilia State University, Tbilisi, Georgia; Eka.gugnashvili1@iliauni.edu.ge
2 Institute of Physics, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria
3 Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria
4 Departament de Física, Universitat de les Illes Balears, E-07122, Palma de Mallorca, Spain
5 Institute of Applied Computing & Community Code (IACC), UIB, Spain
6 High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA

Abstract

Rieger-type periodicity has been detected in different activity indices over many solar cycles. It was recently shown that the periodicity correlates with solar activity having a shorter period during stronger cycles. Solar activity level is generally asymmetric between northern and southern hemispheres, which could suggest the presence of a similar behavior in the Rieger-type periodicity. We analyze the sunspot area/number and the total magnetic flux data for northern and southern hemispheres during solar cycles 19–23, which had remarkable north–south asymmetry. Using wavelet analysis of sunspot area and number during the north-dominated cycles (19–20), we obtained the periodicity of 160–165 days in the stronger northern hemisphere and 180–190 days in the weaker southern hemisphere. On the other hand, south-dominated cycles (21–23) display the periodicity of 155–160 days in the stronger southern hemisphere and 175–188 days in the weaker northern hemisphere. Therefore, the Rieger-type periodicity has the north–south asymmetry in sunspot area/number data during solar cycles with strong hemispheric asymmetry. We suggest that the periodicity is caused by magnetic Rossby waves in the internal dynamo layer. Using the dispersion relation of magnetic Rossby waves and observed Rieger periodicity, we estimated the magnetic field strength in the layer as 45–49 kG in more active hemispheres (north during cycles 19–20 and south during cycles 21–23) and 33–40 kG in weaker hemispheres. The estimated difference in the hemispheric field strength is around 10 kG, which provides a challenge for dynamo models. Total magnetic flux data during cycles 20–23 reveals no clear north–south asymmetry, which needs to be explained in the future.

Key words: Sun: activity – Sun: interior – Sun: magnetic fields

1. Introduction

Short-term variation in gamma-ray flares with a period of 155–160 days was discovered by Rieger et al. (1984) during solar cycle 21. The periodicity later was detected in almost all activity indices (Dennis 1985; Bai & Sturrock 1987; Lean & Brueckner 1989; Bai & Cliver 1990; Lean 1990; Kile & Cliver 1991; Oliver et al. 1998; Ballester et al. 1999; Krivova & Solanki 2002; Dimitropoulou et al. 2008). Carbonell & Ballester (1990) and Carbonell & Ballester (1992) reported the 155-day periodicity in records of the sunspot area during cycles 14–20 and 12–21, respectively. They found that the periodicity was clearly seen during cycles 16–21 but was absent during cycles 12–15. Ballester et al. (2002) analyzed the records of photospheric magnetic flux and found that the periodicity appeared during cycle 21 but was absent in cycle 22.

The Rieger-type periodicity is found also in historical data sets during the earlier cycles. Using two historical auroral data sets, Vaquero et al. (2010) tried to evaluate the presence of Rieger period during cycles 3–4. They have detected the 150-day period in one auroral data set during 1777–1781 (cycle 3), but they could not confirm the same periodicity for cycle 4. Silverman (1990) investigated the occurrence of auroras during the sixteenth and eighteenth centuries and found periods of 158 and 182–185 days for the years of 1570–1572, 1736–1739, and 1787–1790, respectively. Ballester et al. (1999) analyzed the daily number of sunspot groups between 1610 and 1995 and found a nearly 158-day period around the maximum of solar cycle 2. After cycle 2, no strong evidence for the periodicity was found until the twentieth century.

Therefore, the Rieger periodicity of 154 days is not a permanent feature of solar activity, but it varies from cycle to cycle. It was also shown that the periodicity usually appears during 1–3 yr near the cycle maxima and may vary from 130 to 185 days (Lean 1990; Oliver et al. 1998; Zaqarashvili et al. 2010). Recently, Gugnashvili et al. (2016) analyzed long-term sunspot data for solar cycles 14–24 and showed that the Rieger periodicity is anticorrelated with solar cycle strength: stronger cycles show shorter periods. Observed correlation suggests that the periodicity is related to the dynamo layer in the solar interior.

The most promising explanation of the Rieger-type periodicity is connected to magnetic Rossby waves in the solar tachocline (Zaqarashvili et al. 2010). The differential rotation and toroidal magnetic field trigger the instability of spherical harmonics of magnetic Rossby waves with a period of 155–160 days, which leads to the quasi-periodic emergence of magnetic flux toward the surface. The dispersion relation of magnetic Rossby waves depends on the magnetic field strength (Zaqarashvili et al. 2007, 2009); therefore, the observed periodicity should depend on solar activity level, which fairly corresponds to observations (Gugnashvili et al. 2016). Recent discovery of Rossby waves by STEREO and SDO coronal bright point observations (McIntosh et al. 2017) fully confirmed the Rossby wave scenario as a mechanism for Rieger-type periodicity.
Solar activity generally shows north–south asymmetry in many indicators (Spörer 1894; Maunder 1904; Babcock 1959; Waldmeier 1971; Roy 1977; Carbonell et al. 1993; Oliver & Ballester 1994; Li et al. 2002; Temmer et al. 2002, 2006; Ballester et al. 2005; Gigolashvili et al. 2005; McIntosh et al. 2013, 2014, 2015; McIntosh & Leamon 2014), which means that the strength of the cycle is different in northern and southern hemispheres. If the Rieger-type periodicity depends on the activity strength, then it should also display the north–south asymmetry. The different periodicity in northern and southern hemispheres may allow us to estimate the difference in magnetic field strength in the dynamo layer over hemispheres, which might be a clue for the understanding of hemispheric asymmetry.

Here we analyze several available hemispheric activity indices in order to find the values of the Rieger periodicity in northern and southern hemispheres separately during activity cycles that have remarkable north–south asymmetry.

2. North–South Asymmetry in Solar Activity

We use three different data sets to study the north–south asymmetry in the Rieger-type periodicity: (1) Greenwich Royal Observatory (GRO) daily and monthly sunspot area USAF/NOAA data for northern and southern hemispheres (http://solarscience.msfc.nasa.gov/greenwch.shtml), which are available for 1874–2016; (2) Kanzelhöhe Solar Observatory (KSO) and Skalnaté Pleso Observatory (SPO) hemispheric sunspot number data (http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/447/735), which are available in the interval 1945–2004 (Temmer et al. 2006); and (3) the Mount Wilson total magnetic flux (MWTF) data, which are available between 1966 and 2002.

North–south asymmetry was also presented during the Maunder minimum (MM, 1645–1715), when the solar activity was extremely low. Vaquero et al. (2015) and Usoskin et al. (2015) analyzed several data sets, including both direct and indirect data catalogs published by Spörer nearly 130 yr ago, sunspot latitudes in the butterfly diagram during MM published by Ribes and Nesme-Ribes almost 20 yr ago, auroral historical reports during MM, cosogenic radionuclides, etc. They have calculated the asymmetry index using these data sets and confirmed a strong south-dominated hemispherical asymmetry during MM. The Spörer data are given in the paper of Vaquero et al. (2015) and http://haso.unex.es.

We are interested in searching for the Rieger periodicity in the cycles with remarkable north–south asymmetry in order to avoid statistically insignificant correlation between activity and periodicity. Therefore, we first study the long-term north–south asymmetry using GRO sunspot data from 1901 to 2016, which correspond to cycles 14–24, because earlier data are not fully reliable (Erwin et al. 2013; Cliver & Ling 2016; Willis et al. 2016a, 2016b; Cliver 2017). The top panel of Figure 1 shows monthly averaged sunspot area versus time. From colored polygons one can see that the north–south asymmetry is remarkable near the cycle maxima in most cases and different hemispheres dominate at different phases of the corresponding cycle. For example, the southern hemisphere was more active during the ascending and descending phases of cycle 14, while the northern hemisphere was dominating near the cycle maximum. A similar result was previously noticed by Newton & Milsom (1955), who showed that the northern hemisphere was dominant in the early phases of cycles 12–15, with a switch to south dominance later in each cycle. The opposite behavior was found during cycles 17–18. Therefore, full dominance of one hemisphere is not well established. Cycles 19–23 seem to be exceptions, as the asymmetries in these cycles are very strong and can be considered as statistically significant.

Due to the small value of north–south asymmetry in most cycles, it is very important to study the statistical significance. Carbonell et al. (2007) used several data sets and estimated the statistical significance of north–south asymmetry (SSNSA) using different statistical analyses, such as binomial distribution, excess, normal approximation to the binomial distribution, and Pearson’s chi-square test. A similar analysis was performed later by Zhang & Feng (2015).

In order to find the SSNSA in cycles 19–23, we carried out cycle-to-cycle statistical analysis using the binomial distribution (see Table 1)

\[ P_k = \frac{n!}{k!(n-k)!} p^k q^{n-k}, \]

where \( n \) is the total number of sunspot areas, \( k \) is the sunspot area for one hemisphere, \( p \) is the probability for one hemisphere to be stronger, and \( q \) is the probability of another hemisphere. In our case \( p = q = 0.5 \).

When \( P < 0.3\% \), we have a highly significant result; if \( 0.5\% < P < 5\% \), we have a statistically significant result; if \( 5\% < P < 10\% \), it is marginally significant; and when \( P > 10\% \), it is a statistically insignificant result. The results in Table 1 show that the level of asymmetry and its statistical significance are high in cycles 19–23; therefore, we use only the data of these cycles for further analysis. Figure 1 shows that cycles 19–20 are north dominated and cycles 21–23 are south dominated.

3. North–South Asymmetry in Rieger-type Periodicity

As is noted in the previous section, we have three data sets: Greenwich observatory daily sunspot area; the joint catalog of the KSO and SPO, where one can find the daily and monthly sunspot number, as well as smoothed monthly data for both hemispheres separately (Temmer et al. 2006); and the MWTF data (for cycles 20–23, which start from 1965 January and run until 2002 May).

We used the Morlet wavelet analysis (Torrence & Compo 1998) to find the Rieger-type timescale in the three data series. Figures 2–5 show the wavelets of north-dominated and south-dominated cycles, respectively. Figure 2 shows the wavelet analysis performed using GRO data for cycles 19–20. It is clearly seen that the northern hemisphere was dominant in almost the entire cycle (panel a). The Rieger-type timescale in cycle 19 was of order 158–172 days in the northern hemisphere and 172–182 days in the southern hemisphere. Cycle 20 displays the periodicity of 160–165 days in the northern hemisphere and 182–198 days in the southern hemisphere. The cycle-by-cycle global wavelets are computed and plotted alongside each wavelet in sunspot data, where blue (red) color denotes the global wavelet for cycle 19 (20). The global wavelet analysis gives peaks at 160 (180) days in the northern (southern) hemisphere in cycle 19 and at 165 (190) days in the northern (southern) hemisphere in cycle 20. Wavelet analysis reveals that the period of the Rieger-type duration is shorter in the northern hemisphere (by 20–25 days) than the southern one during both cycles.
Figure 3 shows the wavelet analysis of KSO/SPO data during cycles 19–20. The Rieger-type timescale was of order 158–170 days (with a peak at 165 days) in the northern hemisphere and 174–190 days (with a peak at 175 days) in cycle 19. In cycle 20, the Rieger periodicity was 151–156 days (with a peak at 155 days) in the northern hemisphere and 185–190 days (with a peak at 188 days) in the southern hemisphere. KSO/SPO data also show that the stronger northern hemisphere displays shorter periodicity than the weaker southern hemisphere. Hence, the north–south behavior of the Rieger periodicity agrees qualitatively in GRO and KSO/SPO in cycles 19 and 20.

The N–S asymmetry in cycles 21–23 shifted to the southern hemisphere (Verma 1992). We performed the wavelet analysis of the south-dominated cycles separately for sunspot data. Figure 4 represents the wavelet analysis of GRO data for the south-dominated cycles 21–23. The global wavelets are plotted on the right-hand side, where blue, black, and red colors correspond to cycles 21, 22, and 23, respectively. As is expected, the weaker northern hemisphere now shows longer periodicity: 160–187 days (with peak at 183 days) for cycle 21, 168–190 days (with peak at 180 days) for cycle 22, and 170–185 days (with peak at 175 days) for cycle 23. The stronger southern hemisphere displays the shorter periodicity of 155–165 days, with peak at 158, 160, and 160 days for cycles 21–23, respectively (see the Table 2). The difference between hemispheric periodicity is around 15–23 days, very similar to the north-dominated cycles.

Figure 5 shows the wavelet analysis of KSO/SPO data for south-dominated cycles 21–23. The periodicity in the northern hemisphere is of the order of 180–190 days (peak at 188 days) in cycle 21, 175–190 days (peak at 177 days) in cycle 22, and 165–185 days (peak at 174 days) during cycle 23. The stronger southern hemisphere shows the period of 150–165 days, with peaks at 155, 158, and 161 days for cycles 21, 22, and 23, respectively. However, cycle 22 displays another stronger peak at 190 days in the southern hemisphere in both GRO and KSO/SPO data, which is out of the general picture in N–S asymmetry. This interesting disagreement will be discussed later.

Figure 6 presents MWTF data during cycles 20–23 with corresponding wavelet analysis. Panel (a) shows that only cycle 22 displays remarkable N–S asymmetry with the more active southern hemisphere. Cycles 20, 21, and 23 have almost no hemispheric asymmetry. Wavelet analysis gives the periodicity of 160–172 days (with a peak at 168 days) in cycle 20, 160–180 days (with a peak at 170 days) in cycle 21, 165–180 days (with a peak at 175 days) in cycle 22, and 160–175 days (with a peak at 170 days) in cycle 23 in the northern hemisphere. The southern hemisphere shows the periodicity of 158–168 days (with a peak at 165 days) in cycle 20, 180–190 days (with a peak at 187 days) in cycle 21, 150–160 days (with
In cycle 22, and 160–180 days (with a peak at 170 days) in cycle 23. In contrast with GRO and KSO/SPO data, the total magnetic flux shows no clear north–south asymmetry in the Rieger periodicity during cycles 20 and 23. Cycles 21–22 show some N–S asymmetry in magnetic flux, but not as significant as in the sunspot data.

The wavelet analysis of sunspot data (GRO, KSO/SPO) clearly shows that the Rieger timescale is characterized by the hemispheric asymmetry: the stronger hemisphere displays shorter periodicity of the order of 160–165 days, while the weaker hemisphere displays longer periodicity of the order of 175–190 days. This result fairly agrees with the finding of Gurgenashvili et al. (2016) that the stronger cycles generally show shorter periodicity. Here the hemisphere (e.g., northern hemisphere in cycles 19–20 and southern hemisphere in cycles 21–23) with higher activity level has shorter periodicity.

In addition, activity maxima during cycles 19–20 are shifted by 1–2 yr in the northern and southern hemispheres (see Figures 2(a) and 3(a)). The southern hemisphere reaches its maximum before the northern hemisphere during cycle 19, while it is opposite during cycle 20, where the northern hemisphere reaches the maximum first. The north–south phase shift of solar cycles in sunspot data was studied in detail by Dikpati et al. (2007). They showed that the shift of cycle maxima is more pronounced than the shift of minima (see their Figure 5). Our result fairly agrees with their finding. The Rieger periodicity displays a similar phase shift to that seen in Figures 2 and 3. This is in agreement with the previous result that the Rieger periodicity in full disk data appears near the cycle maxima.

On the other hand, the Rieger periodicity shows different behavior in the total magnetic flux. Here no clear north–south asymmetry is seen. Howard (1974) examined magnetic flux data from the Mount Wilson magnetograph during 1967–1973 and reported that the total flux in the north was greater than in the south by only 7%; therefore, asymmetry is missing in the

Figure 2. (a) GRO monthly averaged hemispheric sunspot area for cycles 19–20, with blue (yellow) color representing the case of excess northern (southern) hemisphere. Panels (b) and (c) represent the wavelet of the northern and southern hemisphere, respectively. Global wavelet results are plotted to the right, where blue (red) color corresponds to cycle 19 (20).
MWTF data. Chumak et al. (2003) studied the behavior of the total sunspot area and magnetic flux during the year 1989 and showed that there is not always positive correlation between active regions and total magnetic flux: sometimes the flux increases or decreases, while the sunspot areas remain the same. The difference between the Rieger periodicity in sunspot area/number (GRO, KSO/SPO) and total magnetic flux (MWTF) can be related to the lack of the permanent positive correlation. The lack of correlation might reflect the fact that the total magnetic flux is a sum of strong sunspot and weak plage fluxes, which may have different behavior. During cycle 21, Rabin et al. (1991) found quasi-periodic pulsations only in the strong flux, which were uncorrelated between the hemispheres until 1983, and then they appear to be synchronized. Ballester et al. (2002) studied MWTF data for cycles 20–23 and found a correlation between impulses in strong flux and flares, but not with weak flux. On the other hand, Lean & Brueckner (1989) reported that the Rieger periodicity was not significant in the plage index. This point surely needs more detailed study.

4. Discussion

Rieger-type periodicity has been detected over the past two centuries in different activity indices, which showed that it is not a permanent feature of the solar activity but varies from cycle to cycle. It was recently shown that the Rieger periodicity correlates with solar cycle strength being shorter during stronger cycles, and therefore it could be related to the internal dynamo layer, where strong toroidal magnetic field is generated (Gurgenashvili et al. 2016). Quasi-periodic variation of the dynamo magnetic field with Rieger-type periodicity triggers...
corresponding variations in activity indices owing to the modulation of erupted magnetic flux. If the Rieger periodicity is the feature of the dynamo layer, then it may carry information about its physical parameters.

The mechanism of solar activity still remains as one of the major unsolved problems in solar physics, but the cycles are supposed to be caused by large-scale dynamo action in the solar interior (Charbonneau 2010). The tachocline, the thin layer between radiative and convective envelopes, is suggested to be the location of dynamo action. However, there are also dynamo models without tachocline. The magnetic field strength according to the dynamo models without tachocline is less than 10 kG, but the models with tachocline predict a much stronger field (>10 kG; Charbonneau 2013). Therefore, the estimation

Figure 4. (a) GRO monthly averaged hemispheric sunspot area for cycles 21–23, with blue (yellow) color representing the case of excess northern (southern) hemisphere. Panels (b) and (c) represent the wavelet of northern and southern hemispheres, respectively. Global wavelet results are plotted to the right, where blue, black, and red colors correspond to cycles 21, 22, and 23, respectively.

Table 2

| Cycle Number | Period (N, GRO) | Period (S, GRO) | Period (N, KSO/SPO) | Period (S, KSO/SPO) | Period (N, MWTF) | Period (S, MWTF) |
|--------------|----------------|----------------|---------------------|---------------------|-----------------|-----------------|
| 19           | 158            | 177            | 156                 | 176                 | …               | …               |
| 20           | 165            | 190            | 152                 | 188                 | 168             | 165             |
| 21           | 183            | 158            | 188                 | 155                 | 170             | 187             |
| 22           | 180            | 160            | 177                 | 158                 | 175             | 155             |
| 23           | 175            | 160            | 174                 | 161                 | 170             | 170             |

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of the magnetic field strength is very important, as it may put some limitation on dynamo models in the solar/stellar interiors.

Solar activity displays different levels of activity between the northern and southern hemispheres. This north–south asymmetry is generally small with weak statistical significance, but it becomes remarkable during some (more stronger) cycles. The asymmetry probably reflects the difference between dynamo magnetic field strengths in the northern and southern hemispheres, but the mechanism of the difference is unknown. Even rough estimation of the difference between hemispheric magnetic fields in the dynamo layer may give us a hint toward understanding the triggering mechanism for the asymmetry. The strength of dynamo magnetic field in different hemispheres can be estimated from the observed Rieger periodicity in hemispheric data.

We used the hemispheric data of the GRO daily and monthly sunspot area, joint KSO/SPO daily and monthly sunspot numbers, and the Mount Wilson total magnetic flux to find the Rieger periodicity in northern and southern hemispheres during cycles 19–23, when the north–south asymmetry of solar activity was remarkable (see Figure 1, top panel). Figure 1 shows that the northern hemisphere was much more active during cycles 19–20, but the southern hemisphere became stronger during cycles 21–23. Wavelet analysis of sunspot data (GRO, KSO/SPO) revealed that the Rieger periodicity was significantly different in both hemispheres, being 160–165 days in the northern hemisphere and 175–190 days in the southern hemisphere during the north-dominated cycles, while it became 155–160 days in the northern hemisphere and 175–188 days in the southern hemisphere during the south-dominated cycles (see Table 2 for details). Therefore, the periodicity clearly reflects the north–south asymmetry in solar activity.

Sturrock et al. (1999) suggested that the Rieger periodicity might be caused by \( r \)-modes of rotating Sun, which are hydrodynamic (HD) Rossby waves. Then, Lou (2000) suggested an explanation for the periodicity in terms of
equatorially trapped HD Rossby waves. However, the periodicity is usually observed in activity indices; hence, the magnetic field should be clearly involved in the scenario. Zaqarashvili et al. (2010) showed that the Rieger periodicity is related to the instability of magnetic Rossby waves, due to the differential rotation and toroidal magnetic field in the dynamo layer. Therefore, the observed periodicity alongside the dispersion relation of magnetic Rossby waves could lead to the estimation of dynamo magnetic field in individual cycles. Based on the magnetic Rossby wave theory, Gurgenashvili et al. (2016) estimated a magnetic field strength in the dynamo layer of $\approx 40$ kG during stronger solar cycles (16–23) and $\approx 20$ kG during weaker cycles (14–15 and 24).

The dispersion relation of fast magnetic Rossby waves (the slow magnetic Rossby waves may lead to the long-term variation of solar cycles, as suggested by Zaqarashvili et al. 2015) in the dynamo layer can be written as (Gurgenashvili et al. 2016)

$$\omega_{f} = -m\Omega_0 \frac{1 + s_2 + \sqrt{(1 + s_2)^2 + \frac{4B_{\text{max}}^2}{4\pi\rho\mu_0 R_0^2} n(n + 1)}}{n(n + 1)},$$

where $\omega_{f}$ is the frequency of fast magnetic Rossby waves, $\Omega_0$ is the equatorial angular velocity, $s_2$ is the parameter of the differential rotation, $\rho$ is the density, $R_0$ is the distance from the solar center to the dynamo layer, $B_{\text{max}}$ is the dynamo magnetic field strength at $45^\circ$, and $m$ and $n$ are toroidal and poloidal wavenumbers, respectively. Only the magnetic field strength is an unknown parameter in the dispersion relation; therefore, it can be deduced from the observed periodicity. Gurgenashvili et al. (2016) showed that the spherical harmonic with $m = 1$ and $n = 4$ may confidently explain the observed periodicity for the 30–50 kG magnetic field.
We use the dispersion relation (Equation (2)) for estimation of magnetic field strength in the northern and southern hemispheres during cycles 19–23. The differential rotation parameters were not estimated for the northern and southern hemispheres separately for these cycles; therefore, initially we set \( s_2 = 0 \) in Equation (2). Based on the GRO data, we calculate the maximum magnetic field strength as 48 kG (38 kG) in the northern (southern) hemisphere during north-dominated cycle 19, 45 kG (33 kG) in the northern (southern) hemisphere during north-dominated cycle 20, 49 kG (36 kG) in the southern (northern) hemisphere during south-dominated cycle 21, 48 kG (38 kG) in the southern (northern) hemisphere during south-dominated cycle 22, and 48 kG (40 kG) in the southern (northern) hemisphere during south-dominated cycle 23. These calculations show that the difference between dynamo magnetic field strengths in northern and southern hemispheres during cycles 19–23 is of the order of 10 kG, which is a quite significant value (see Figure 7). Nonzero differential rotation parameter \( s_2 \) in Equation (2) changes the estimated value of magnetic field strength (see the Table 3); however, the hemispheric difference still remains of the order of 10 kG. It must be mentioned, however, that the estimation of magnetic field strength is rather rough, and future detailed analysis (including numerical simulations) is needed to increase the accuracy. Figure 7 shows that the estimated magnetic field strength does not significantly vary during cycles 21–23, while the cycle amplitude has been continuously declining. This may support the evidence that the sunspot cycle is an “interference” pattern of overlapping 22 yr bands (McIntosh et al. 2014). Moreover, it is seen from Figure 7 that the difference between southern and northern hemispheric magnetic field strengths is also decreasing, which could be a result of interaction of the bands. This point needs detailed study in the future.

The estimated large difference between dynamo field strengths in the two hemispheres needs to be explained in the future. It may become a key point for resolving the problem of solar dynamo and activity cycles. It is possible that the observed north–south asymmetry is due to the overlapping of the 11 yr oscillating dynamo magnetic field with some steady field component. In this case, the steady field of 5 kG may cause the required 10 kG difference in the hemispheric magnetic field. Dikpati et al. (2006) showed that the steady (nonreversing) toroidal field can be generated in the lower tachocline, due to a steady dynamo in the case of low magnetic diffusivity with a strength of \( >1 \text{kG} \), which is in the range of the required value. Then the temporal variation of the nonreversing magnetic field with longer timescales caused by slow magnetic Rossby waves below the solar tachocline (Zaqarashvili et al. 2015) may lead to the observed variations in north–south asymmetry. This is, however, only speculation, and no real physical mechanism resolving the north–south asymmetry problem exists up to now. Recent flux transport

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**Figure 7.** Top panel: cycle-averaged sunspot area for cycles 19–23 (based on GRO data), where the red (black) line corresponds to the northern (southern) hemisphere. Bottom panel: estimated magnetic field strength in the northern (red) and southern (black) hemispheres for cycles 19–23.

**Table 3**

| Cycle Number | 19 | 19 | 20 | 20 | 21 | 21 | 22 | 22 | 22 | 23 | 23 |
|--------------|----|----|----|----|----|----|----|----|----|----|----|
| Differential Rotation, \( s_2 \) | 0.19 | 0 | 0.16 | 0 | 0.14 | 0 | 0.14 | 0 | 0.17 | 0 |

|                      | north          | south          |
|----------------------|----------------|
| \( B_{\text{max}} \) (kG) | 40 | 28 |
| \( B_{\text{max}} \) (kG) | 49 | 39 |

*Note.* The meanings of differential rotation parameter \( s_2 \) are obtained by Javaraiah et al. (2005).
dynamo simulations have addressed this problem in terms of N/S asymmetries in the surface poloidal source (Beluč et al. 2013) and in meridional circulation (Beluč & Dikpati 2013), but the reason for such asymmetries in the dynamo ingredients is yet to be physically explored.

It must be noted here that the sunspot number data in cycle 22 display the significant peak at a longer period (~190 days) in the southern hemisphere, which is somehow out of regularity. This long-period peak may correspond to the higher harmonic of magnetic Rossby waves. For example, if the shorter period of 158 days is caused by the $m = 1$, $n = 4$ harmonic (as suggested above), then the harmonic with $m = 1$, $n = 5$ would give a period of ~210 days, which is not far from the observed peak. The long-period peaks can be seen also in other cycles and might correspond to the regular pattern. This requires further detailed study.

In contrast with sunspot number/area data, total magnetic flux does not show any remarkable north–south asymmetry in the Rieger periodicity. Therefore, it seems that the total magnetic flux does not clearly manifest the north–south asymmetry. This is probably caused by the fact that the used MWTF contains both strong sunspot flux and weak plage flux, from which only the strong flux has N–S asymmetry. This is an interesting question to be answered in the future.

5. Conclusions

We carried out the wavelet analysis of the hemispheric sunspot area (GRO), sunspot number (KSO/SPO), and MWTF data during solar cycles (19–23) with remarkable north–south asymmetry: the northern hemisphere was dominated during cycles 19–20, and the southern one was dominated during cycles 21–23. The analysis of sunspot area/number data showed that the Rieger-type periodicity is also asymmetric with hemispheres. We obtained the periods of 160–165 days in the northern hemisphere and 180–190 days in the southern hemisphere during cycles 19–20, while we obtained periods of 155–160 days in the northern hemisphere and 175–188 days in the southern hemisphere during cycles 21–23. Therefore, the Rieger-type periodicity in sunspot area/number data correlates with hemispheric activity levels in the same sense as it correlates with cycle strength based on full disk data (Gurgenashvili et al. 2016): the hemisphere with stronger activity displays the periodicity with shorter period. Hence, the Rieger periodicity is connected to the internal dynamo layer, where the magnetic field and the solar cycles are generated.

The magnetic field might be modulated by magnetic Rossby waves, which leads to the quasi-periodic emergence of magnetic flux. This scenario is fully supported by recent direct observations of Rossby waves using Stereo and SDO coronal bright point data (McIntosh et al. 2017). In addition, activity manifests a phase shift of 1–2 yr between northern and southern hemispheres, which is clearly seen during cycles 19–20 (see more detailed analysis in Dikpati et al. 2007). The Rieger periodicity also takes place at different times (with a similar 1–2 yr shift) in the two hemispheres, which means that the quasi-periodic flux emergence correlates with the maximum phase of solar cycles. The obtained periodicity and the dispersion relation of magnetic Rossby waves were used to estimate the magnetic field strength in the tachocline as 45–48 kG in the more active hemisphere (the northern hemisphere during cycles 19–20 and the southern one during cycles 21–23) and 32–38 kG in the weaker hemisphere. The north–south difference in the dynamo magnetic field strength is almost 10 kG, which reaches to almost 25% of the estimated magnetic field. The significant hemispheric difference of the field strength induces future challenges for dynamo models.

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ORCID iDs

Eka Gurgenashvili © https://orcid.org/0000-0003-0162-6083
Teimuraz V. Zaqrashvili © https://orcid.org/0000-0001-5015-5762
Vasil Kukhianidze © https://orcid.org/0000-0003-0660-8669
Ramon Oliver © https://orcid.org/0000-0003-4162-7240
Jose Luis Ballester © https://orcid.org/0000-0001-8921-9225
Mausumi Dikpati © https://orcid.org/0000-0002-2227-0488
Scott W. McIntosh © https://orcid.org/0000-0002-7369-1776

References

Babcock, H. D. 1959, ApJ, 130, 364
Bai, T., & Cliver, E. H. 1990, Apj, 363, 299
Bai, T., & Sturrock, P. A. 1987, Natur, 327, 601
Ballester, J. L., Oliver, R., & Baudin, F. 1999, ApJL, 522, L153
Ballester, J. L., Oliver, R., & Carbonell, M. 2002, ApJ, 566, 505
Ballester, J. L., Oliver, R., & Carbonell, M. 2005, A&A, 431, L5
Beluč, B., & Dikpati, M. 2013, ApJ, 779, 4
Beluč, B., Forgács-Dajka, E., & Dikpati, M. 2013, AN, 334, 960
Carbonell, M., & Ballester, J. L. 1990, A&A, 238, 377
Carbonell, M., & Ballester, J. L. 1992, A&A, 255, 350
Carbonell, M., Oliver, R., & Ballester, J. L. 1993, A&A, 247, 497
Carbonell, M., Terradas, J., Oliver, R., & Ballester, J. L. 2007, A&A, 476, 951
Charbonneau, P. 2010, LRSP, 7, 3
Charbonneau, P. 2013, JPhCS, 440, 012014
Chumak, O., Obridko, V., Zhang, H., et al. 2003, A&A, 42, 335
Cliver, E. W. 2017, JSWSC, 7, A12
Cliver, E. W., & Ling, A. G. 2016, SoPh, 291, 2763
Dennis, B. R. 1985, SoPh, 100, 465
Dikpati, M., Gilman, P. A., de Toma, G., & Ghosh, S. S. 2007, SoPh, 245, 1
Dikpati, M., Gilman, P. A., & MacGregor, K. B. 2006, ApJ, 638, 564
Dimitropoulou, M., Moussas, X., & Strintzis, D. 2008, MNRA, 386, 2278
Erwin, E. H., Coffey, H. E., Denig, W. F., et al. 2013, SoPh, 288, 157
Gigolashvili, M. Sh., Japaridze, D. R., Mdzinarishvili, T. G., & Chargieishvili, B. B. 2005, SoPh, 227, 27
Gurgenashvili, E., Zaqrashvili, T. V., Kukhianidze, V., et al. 2016, ApJ, 826, 55
Howard, R. 1974, SoPh, 38, 59
Javaraiah, J., Bertello, L., & Ulrich, R. K. 2005, SoPh, 232, 25
Kile, J. N., & Cliver, E. W. 1991, ApJ, 370, 442
Krivova, N. A., & Solanki, S. 2002, A&A, 394, 701
Lean, J. L. 1990, ApJ, 363, 718
Lean, J. L., & Brueckner, G. E. 1989, Apj, 337, 568
Li, K. J., Wang, J. X., Xiong, S. Y., et al. 2002, A&A, 383, 648
Lou, Y. Q. 2000, ApJ, 540, 1102
Mander, E. W. 1904, MNRAS, 64, 747
McIntosh, S. W., Cramer, W. J., Marcano, M. P., & Leamon, R. J. 2017, NatAs, 1, 0086
McIntosh, S. W., & Leamon, R. J. 2014, ApJL, 796, L19
