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Hemispheric Asymmetry of the Solar Dynamo

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Abstract

The solar dynamo transforms the poloidal solar magnetic field prevailing during sunspot minimum into toroidal field which gives rise to sunspots, and back. The transition of poloidal into toroidal field is due to the differential rotation at the base of the convection zone which stretches the North-South magnetic field lines into East-West direction. Two mechanisms are responsible for the recreation of the poloidal from the toroidal field: turbulent diffusion, and large-scale meridional circulation. The dynamo's regime of operation depends of the relative importance of these two mechanisms. If both are operational, the sunspot number has two maxima during the solar cycle: one diffusion-generated, the other one advection-generated.

Earlier we found that, averaged over the two solar hemispheres, the diffusion-generated peak seems to appear earlier and at higher heliolatitudes than the advection-generated one in all sunspot cycles from 15 to 19. The order is reversed in cycles 12-14 and 20-23.

Here we repeat this study separately for the two solar hemispheres, and compare the two Gleissberg cycles minima between the 19th and 20th centuries, and between the 20th and 21st centuries. We find that the solar dynamo did not operate in different regimes during the last two Gleissberg minima. Moreover, it does not operate in different regimes during these secular minima and the cycles between them. An unexpected result is that the evolution of sunspot activity generated by diffusion and advection is different in the Southern and Northern hemispheres. The pattern is the same in all studied cycles with the exception of cycle 19 – the cycle of the secular sunspot maximum, which is quite peculiar.

Keywords: solar dynamo; Gnevyshev gap; hemispheric asymmetry

1. Introduction

Solar cycles are fundamental to our understanding of solar activity and have a direct impact on all aspects of solar-terrestrial interactions. Each of these periods is characterized by a systematic increase and decrease in the number of sunspots, which corresponds to changes in the Sun's magnetic field. Understanding solar cycles is crucial not only for solar science but also for predicting space weather, which can have direct effects on satellite communications, navigation, space travel, and Earth's energy infrastructure. Therefore, they are of interest not only academically but also as a practical necessity for contemporary society.

Sunspots are visible indicators of solar activity and magnetism. Their number and distribution change over each cycle and are associated with various solar phenomena, including solar flares which can disrupt communications, and the eruptions of solar plasma known as coronal mass ejections (CMEs), which can significantly affect space weather and Earth's technological systems.

The most prominent cyclicity of solar activity is the ~11-year ("Schwabe") sunspot cycle. The Schwabe cycles are not all the same, but vary in both amplitude and duration, modulated by a secular cycle known as the "Gleissberg cycle" (Gleissberg, 1930).

Some ~11-year sunspot cycles feature a single maximum, while others have two maxima. Long ago it was found that all cycles are double peaked (Gnevyshev, 1963; Antalova and Gnevyshev, 1965), with the two peaks observed at different latitudes and supposedly caused by different physical mechanisms. Moreover, even if the solar activity progresses differently in the two hemispheres which leads to two peaks in global averages, two separate peaks are also observed in each of the hemispheres. Using the superposed method analysis for all eight sunspot cycles from 1874 to 1962, Antalova and Gnevyshev (1965) concluded that in all cycles the first peak appears simultaneously at all latitudes, and the second one only at low latitudes. Their relative amplitude and the time between them vary, therefore in some cycles they can be seen as a single peak in time averages, in other cycles the gap between them known as "Gnevyshev gap" is clearly seen.

Georgieva (2011) proposed an explanation of the two peaks. As is well known, in the course of the solar cycle sunspots appear in bipolar pairs at lower and lower heliolatitudes with the leading (in the direction of solar rotation) sunspot at lower heliolatitudes and with the polarity of the respective pole, and the trailing sunspot at higher heliolatitudes and with the opposite polarity. According to the flux-transport solar dynamo mechanism (Babkock, 1961; Leighton, 1964; Wang, 1991), late in the sunspot cycle when the sunspot pairs appear close to the equator, the leading polarity spots in each hemisphere diffuse across the equator and cancel with the opposite polarity spots of the other hemisphere. The trailing polarity spots of these sunspot pairs and the remaining complete pairs are carried poleward where they first cancel the polar field of the old cycle and then accumulate to form the opposite polarity field of the new cycle.

Two processes are responsible for this transport: supergranular diffusion, and large-scale meridional circulation, poleward at the surface and equatorward at the base of the convection zone where it carries like a conveyor belt the poloidal field which is there transformed by the differential rotation into toroidal field and emerges at lower and lower latitudes as sunspots of the new cycle. The regime of operation of the solar dynamo depends on their relative importance in carrying the flux to the pole. If the time scale of the meridional circulation is much shorter than the diffusion time scale (advection dominated regime), all of the flux will pass the whole way on the surface to the pole where it will reverse the polar field and then sink to the base of the convection zone. If the diffusion time scale is much shorter (diffusion dominated regime), all of the toroidal field is generated from the flux which has diffused to the base of the convection zone, shortcircuiting the merifional circulation. Only a small part of the trailing polarity flux reaches high latitudes before being diffused, and reverses the polar field there. In the intermediate case when neither of the two mechanisms is much more efficient than the other, some of the magnetic flux shortcuts the meridional circulation and diffuses directly to the bottom of the convection zone at mid-latitudes. Another part of the flux follows the path all the way to the poles, down to the base of the convection zone, and then equatorward to latitudes where sunspots tend to form (Figure 1). Estimations of the diffusivity and meridional circulation (Georgieva and Kirov, 2011) show that this is the regime in which solar dynamo has been recently operating. This leads to two surges of toroidal field: one generated by the flux shortcircuiting the meridional circulation due to diffusion, and one generated by the flux making the full circle poleward at the surface, down to the bottom of the convection zone at high latitudes, and equatorward from there. The diffusion-related peak appears simultaneously at a broad range of latitudes, while the advection-related one moves equatorward with time (Yeates et al., 2008). The order in which these two peaks appear, the time between them, and their relative amplitudes depend on the relative importance of diffusion and advection.

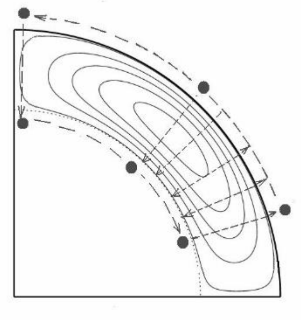

Figure 1. *Intermediate regime: a part of the flux diffuses through the convection zone, "short-circuiting" the meridional circulation, another part makes a full circle to the poles, down to the base of the convection zone and equatorward to sunspot latitudes.*

2. Data

For quantifying sunspot activity we use the sunspot area in 50 latitude bins distributed uniformly in Sine (latitude) for each Carrington rotation since 1874. This is the well known "Butterfly diagram" provided by Dr. David Hathaway from Stanford University (http://SolarCycleScience.com/).

3. Results

A comparison of cycle 12/14, and cycles 23/24 shows that both cycles 23 and 24 during the recent Gleissberg minimum have well expressed doule sunspot maxima, while the cycles during the previous Gleissberg minimum are almost all (with the exception of cycle 12) characterizes by single maxima (Figure 2).

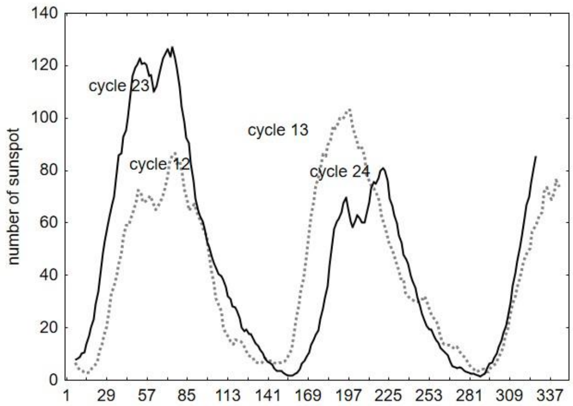

Figure 2. *A comparison between cycles 12-14 during the 19-20th century Gleissberg minimum (dotted line) and cycles 23-25 during the 20-21st century Gleissberg minimum (solid line). X-axis: months since the beginning of the period studied; Y-axis: sunspot number (V1.0)*

To elucidate the temporal variation in sunspot activity, Figures 4 and 5 demonstrate the evolution of the latitude-time variations of the sunspot areas in the two hemispheres (upper panels), of global latitude-time sunspot areas (middle panels), and of the respective global averages for cycles 12-14 and 23-24, respectively.

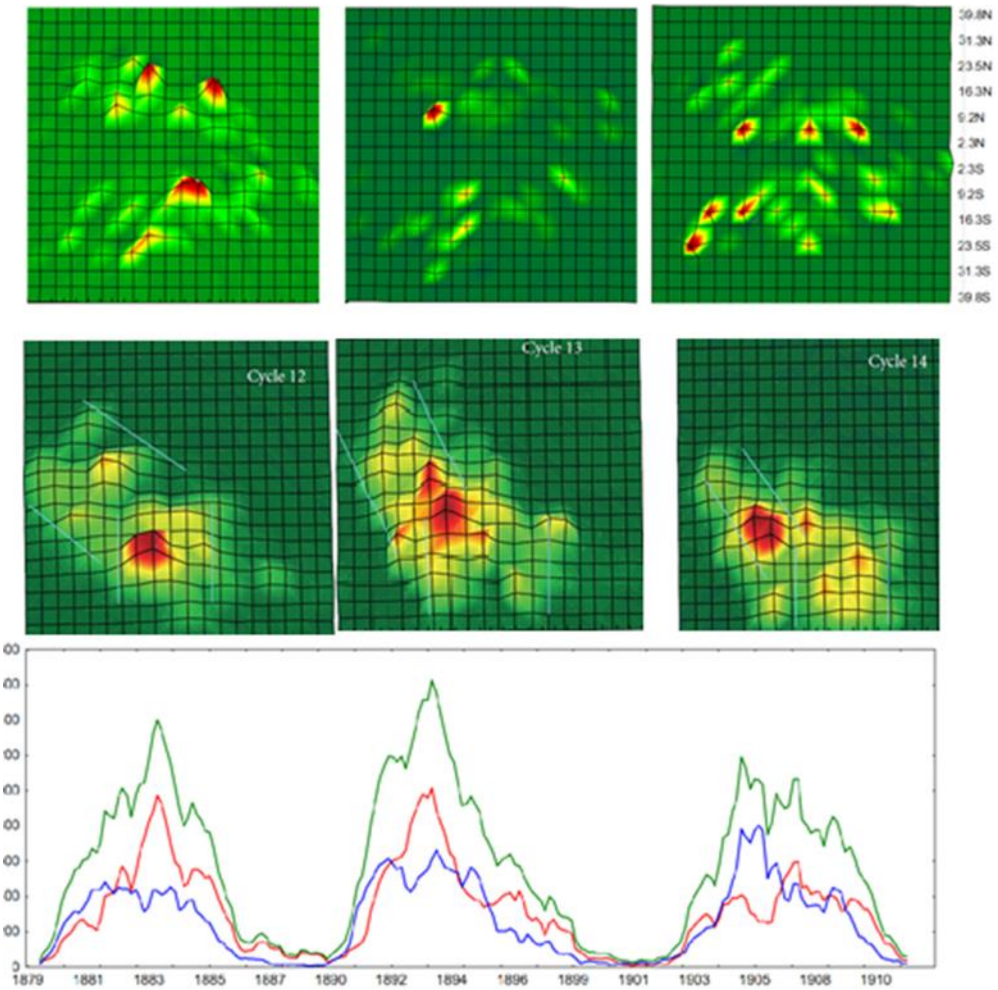

Figure 3. *Latitude-time evolution of sunspot area for sunspot cycles 12 – 14. Upper panel: in the two hemispheres; middle panel: averaged over the whole disk; bottom panel: green line – total sunspot area; red line – Southern hemisphere sunspot area; blue line – Northern hemisphere sunspot area.*

In cycle 12, the first surge (or rather a number of surges) of sunspots in the Southern hemisphere appeared at about 30o and moved equatorward. We identify this as the advection-generated sunspot activity region (Yeates et al., 2008). This region then merged with a second surge which appeared later in a wide range of latitudes with a peak at about 9^o, and persisted between 2^o and 26^o, slowly moving to the equator. We identify it as the diffusion-generated sunspot activity region. In the Nortern hemisphere, the sunspots first emerged in a broad latitudinal region between about 9 and 25^o with a maximum around 16^o, and persisted there (diffusion-generated), and the second surge started later at about 20^o and moved equatorward (advection-generated). The situation is similar in the following two cycles: first an advection-related peak followed by a diffusion-related peak in the Southern hemisphere, first a diffusion-related followed by an advection-relaated peak in the Northern hemisphere. In cycle 12 there is some time between the two surges in both hemispheres, so in global averages a clear Gnevyshev gap is observed. In cycles 13 and 14 the surges of sunspot appearance overlap, and distinctly separated maxima are not observed in global averages. In all three cycles the diffusion-generated peak is higher than the advection-generated one, and it determines the peak in global average.

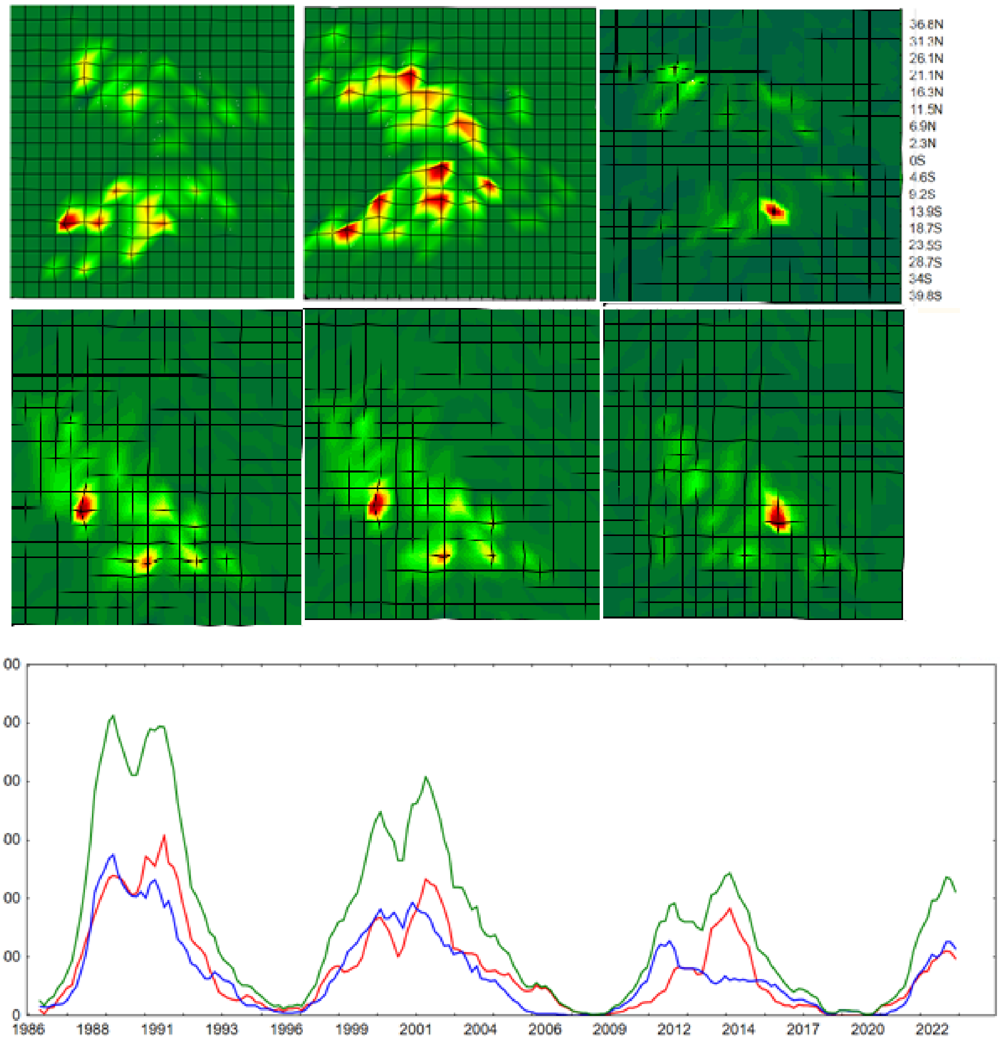

Figure 4. *The same as Figure 2 for cycles 22-24.*

In cycle 23 (Figure 4), the first sunspot surge in the Southern hemisphere was again advection-related. It started at about 30o and moved to the equator, on the way merging with the diffusion-related peak which emerged later between 28^o and 2^o. In the Northern hemisphere, the diffusion-generated surge started first at about 26^o and expanded to about 2^o, followed by a couple of advection-generated surges which continued for about 50 rotations. In the global average, the first sunspot peak was due to the superposition of the Southern hemisphere advection-generated maximum and the Northern hemisphere diffusion-generated maximum, while the second and higher one – mostly due to the Southern hemisphere advection-generated maximum.

In cycle 24 the advection-generated peak in the Southern hemisphere started at 24^o, moved slowly almost to the equator, to 11^o. At about 11^o this advection-generated peak merged with the much stronger diffusion-generated peak spanning from 30^o to 7^o and persisting for many rotations until the end of 2018, a year before the start of the following cycle. The first, diffusion-generated peak, in the Northern hemisphere was also much stronger than the subsequent two advection-generated peaks. As a result, the global picture was dominated by the diffusion-generated peaks in the two hemispheres which were well separated in time, so a clear Gnevyshev gap was observed. It was in this case due not to the two distinct peaks in each of the hemispheres, but to the superposition of the dominant peaks in the two of them.

Also shown in Figure 4 for comparison is cycle 22 (1986-1996) where the first global sunspot maximim is due to the superposition of the advection-generated Southern hemisphere maximum and the diffusion-generated Northern hemisphere maximum, while the second global sunspot maximim is due to the superposition of the diffusion-generated Southern hemisphere maximum and the advection-generated Northern hemisphere maximum.

In summary, in both 19/20 and 20/21 century Gleissberg minima, each sunspot cycle began with an advection-generated followed by a diffusion-generated peak in the Southern hemisphere, and by a diffusion-generated followed by an advection-generated peak in the Northern hemisphere.

We have also checked the evolution of the sunspot activity in the two solar hemispheres for all cycles for which data are available (since 1874 up to present time, (http://SolarCycleScience.com/). We have found that the same pattern is observed in all sunspot cycles (not shown) with the exception of cycle 19 – the cycle of the secular sunspot maximum, which is quite a peculiar cycle.

4. Discussion

Some sunspot cycles have a single maximum in the number and area of sunspots, as well as in other manifestations of solar activity, while others are double peaked. Gnevyshev (1963) used the intensity of the coronal line 5303 Å at different heliolatitudes from 1954 to 1962 (sunspot cycle 19) and found that though the cycle featured a single maximum when averaged over all latitudes, the coronal intensity had actually two maxima: a first one at all latitudes, and then a second one only at low latitudes. Similar temporal distribution was found also in the data on sunspots and prominrnces, which led to the conclusion that these two maxima in the 11-year sunspot cycle are characteristic not only of the solar corona but of all layers in the solar atmosphere (Gnevyshev, 1963).

The 5303 Å coronal emission has been measured since 1939. To study the evolution of the sunspot cycles on a longer time-scale, Antalova and Gnevyshev (1965) used the sunspot areas published in the Greenwich Data Catalog from 1874 to 1958, and in the Pulkovo Solar Acrivity Catalog from 1959 until 1962, and found that actually all cycles are double peaked when looked at different latitudes. If the time between the peaks is short, they appear as a single peak in the time/latitude averages. If the peaks are well separated in time, the gap between them known as “Gnevyshev gap” is clearly seen. Using the superposed method analysis for all cycles from 12 to 19 at different latitudes, Antalova and Gnevyshev (1965) concluded that in all studied cycles the first peak appears simultaneously at all latitudes, and the second one only at low latitudes.

Gnevyshev (1963) speculated that the two peaks may be caused by different physical mechanisms. At that time the possible physical mechanisms causing peaks in sunspot acyivity were not identified. As mentioned in the Introduction, according to the Babkock-Leighton flux-transport solar dynamo mechanism (Babkock, 1961; Leighton, 1964), when the leading polarity spots in each hemisphere diffuse across the equator and cancel with the opposite polarity leading spots of the other hemisphere, the trailing polarity spots of these sunspot pairs and the remaining complete pairs are carried poleward by turbulent diffusion to first cancel the polar field of the old cycle and then accumulate to form the opposite polarity field of the new cycle. In the Babkock-Leighton flux-transport solar dynamo mechanism, turbulent diffusion was originally considered the only factor to transfer the toroidal field of a cycle into opposite-polarity poloidal field of the next cycle. Later Wang et al. (1991) proposed the large-scale meridional circulation as another important factor with a surface flow toward the poles where the poloidal field of the next cycle is generated with polarity opposite to the one in the preceding cycle, then the flow sinks to the base of the convection zone, and is carried equatorward by the counterflow there, on the way generating the toroidal field of the next cycle. The regime of operation of solar dynamo depends on the relative importance of diffusion and advection (meridional transport). If both factors are at work, the sunspot activity will have two peaks in the course of the solar cycle: diffusion-generated and afvection-generated (Georgieva, 2011). The diffusion-generated peak appears nearly simultaneously at all latitudes, and the afvection-generated one moves with time to the equator (Yeates et al., 2008).

The observation of Antalova and Gnevyshev (1965) that in all cycles the first peak (diffusion-generated) appears simultaneously at all latitudes, and the second one (advection-generated) only at low latitudes, was based on data averaged over the whole solar disk and over all cycles from 12 to 19 (superposed analysis). In the present study we looked at the sunspot activity evolution separately in the two solar hemispheres based on sunspot area data since 1874, and found that since cycle 12, in all cycles there is a well expressed hemispheric asymmetry: first an advection-related peak followed by a diffusion-related peak in the Southern hemisphere, first a diffusion-related followed by an advection-related one in the Northerm hemisphere. This pattern is the same during the last two Gleissberg minima (cycles 12-14, and 22-24, respectively), and the cycles between them, with the exception of cycle 19 in the secular solar maximum, which is anomalous in several respects and has long been recognized as peculiar. This means that there is no evidence that the global dynamo switched operating regimes between those secular minima.

Helioseismology further supports a hemispheric pathway to asymmetry. Long-term measurements reveal persistent north–south asymmetries in torsional oscillations that precede and correlate with hemispheric asymmetries in surface activity; the velocity asymmetry leads flux/sunspot asymmetry, suggesting a causal link (Lekshmi, Nandy & Antia, 2018; 2019). Such flow asymmetries provide a plausible physical conduit by which modest, early-cycle differences in deep-seated dynamics are amplified into measurable hemispheric phasing and amplitude differences at the surface—consistent with our finding that the diffusion-first versus advection-first sequencing can differ by hemisphere.

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