

Global solar photospheric and coronal magnetic field over activity cycles 21–25

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Abstract—The evolution of the global solar magnetic field from the beginning of cycle 21 (mid-1970s) until the currently-ascending cycle 25 is described using photospheric full-disk and synoptic magnetograms from NSO Kitt Peak Vacuum Telescope (KPVT) 512-channel and Spectromagnetograph (SPMG) and the Synoptic Optical Long-term Investigation of the Sun (SOLIS) Vector Spectro-Magnetograph (VSM) and Global Oscillations Network Group (GONG), and Stanford University's Wilcox Solar Observatory (WSO). The evolving strength and symmetry of the global coronal field are described by potential-field source-surface models decomposed into axisymmetric and non-axisymmetric, and even- and odd-ordered magnetic multipoles. The overall weakness of the global solar magnetic field since cycle 23 splits the 50-year observing window into the stronger, simpler, more hemispherically symmetric cycles 21 and 22 and the weaker, more complex cycles 23 and 24. An anomalously large decrease in the global solar field strength occurred during cycles 23, and an anomalously weak axial/polar field resulted from that cycle, accompanied by an anomalously weak radial interplanetary magnetic field (IMF) during cycle 23 activity minimum and a weakened radial IMF overall since cycle 23. The general long-term decline in solar field strength and the development during cycle 24 of strong swings of hemispheric and polar asymmetry are analyzed in detail, including their transfer through global coronal structural changes to dominate mean in situ interplanetary field measurements for several years. Although more symmetric than cycle 24, the rise phase of cycle 25 began with the southern leading the northern hemisphere, but the north has recovered to lead this cycle's polar field reversal. The mean polar flux (poleward of $\pm 60^\circ$) has reversed at each pole, so far more symmetrically than the cycle 23 and 24 polar reversals.

Keywords: Sun / Corona / Photosphere / Magnetic field / Solar cycle

1 Introduction

The Sun's photospheric magnetic field determines the global structure of the corona and heliosphere. Understanding global solar magnetic field evolution is therefore key to determining the causes of major long-term heliospheric change. Across numerous solar and heliospheric physical parameters and indices, including the sunspot number¹, the solar polar field (Petrie, 2015), and the radial IMF (Smith & Balogh, 2008), the global solar and heliospheric field has become progressively weaker over the past several cycles. The polar fields, both north and south, have been only about 60% as strong since the cycle 23 polarity reversal compared to before (Petrie, 2015), and there was a 30%–40% drop in IMF from cycle 22 to cycle 23 solar minimum (Smith & Balogh, 2008) leading to a change in the physical properties and geoeffectiveness of coronal mass ejections (CMEs Gopalswamy et al., 2014, 2015).

(We adopt the convention that the activity minimum is named for the sunspot cycle maximum that it follows.) These developments are consistent with each other and seem to be connected with not only a longer-term decrease in the amplitude of activity cycles up to cycle 24, but also a particular change in the flux emergence patterns during the decline of cycle 23, when the mean Joy's law tilt angle of bipolar ARs became small, stunting the growth of the polar fields during that cycle (Petrie, 2012).

This weakening of the global solar field was accompanied by greater complexity of structure in the photosphere and corona, with less dominance of lower-order spherical harmonics in potential-field source-surface (PFSS; Altschuler & Newkirk, 1969; Schatten et al., 1969) coronal field models (Petrie, 2013; Virtanen & Mursula, 2017), and a larger ratio of low- to high-latitude coronal hole coverage (de Toma, 2011). Cycles 23 and 24 featured more asymmetric polar field reversals than cycles 21 and 22, with the north pole reversing much more slowly than the south during cycle 23, and vice versa during

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¹ Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

cycle 24. Between cycles 23 and 24, the cycle 24 polar asymmetry was the more prominent: during that cycle's polar reversal the north polar field marked time close to zero for several years, changing sign multiple times, while the south reversed swiftly and straightforwardly (Petrie, 2023). The north and south hemispheric fluxes also changed sign multiple times during this complex polar field reversal. We will show in this paper that this uniquely strong asymmetry carried over to the global coronal magnetic field structure and to the radial IMF component near Earth for several years.

Petrie (2023) analyzed the relationship between photospheric flux transport and polar field evolution by adapting a technique of Durrant et al. (2004) to time series of full-disk magnetogram data. With a moderate supergranular diffusion rate $\eta = 600 \text{ km}^2 \text{ s}^{-1}$, the largest poleward flux surges were found to originate close in time to activity cycle maxima, from the usual latitude range for ARs during activity cycle maximum, $\approx \pm 10^\circ - \pm 30^\circ$. Peak levels of flux emergence allowed peak levels of leading-polarity flux to cancel or migrate across the equator, leaving peak levels of trailing-polarity flux to travel polewards, producing the largest polar field changes. The asymmetric development of cycle 24 displayed an important departure from this pattern: the three-part asymmetric flux-emergence pattern of this cycle, with the northern hemisphere initially dominant, followed by a strong, brief, dominant activity maximum in the south, and finally, a declining phase again dominated by the north, enabled not only leading-polarity flux but also trailing-polarity flux to cross the equator in much greater quantities than observed during the previous three cycles, producing fast-changing hemispheric flux asymmetries and successive trans-equatorial flux transport swings of opposite sign. We will show that one can trace these hemispheric changes through the coronal structure to the radial IMF near Earth uniquely clearly during cycle 24.

The standard way to study the global solar field over several solar activity cycles is to apply synoptic data products from long-term synoptic observing programs, which have been observing the full solar disk routinely for the past several decades. At Mt. Wilson, the first such synoptic observing program began (Howard, 1967) with daily full-disk synoptic magnetogram observations, from which full-surface synoptic magnetograms were constructed (Howard, 1989). Similar programs were introduced at NSO Kitt Peak (Livingston et al., 1976, Harvey et al., 1980) and at Wilcox Solar Observatory (WSO; Svalgaard et al., 1978) in the 1970s. Several instrument upgrades occurred at NSO (Keller et al., 2003): the Kitt Peak Vacuum Telescope 512-channel (1974–1993) and Spectro-Magnetograph (1992–2003) instruments were succeeded by the Synoptic Optical Long-term Investigations of the Sun Vector Spectro-Magnetograph (SOLIS/VSM). The Global Oscillations Network Group (GONG) helioseismology Dopplergraph instrument was adapted to produce science-quality longitudinal magnetograms by adding a quarter-wave plate (2006–present; Hill, 2018). The six ground-based GONG telescopes have provided these LOS magnetograms continuously since 2006. The Solar and Heliospheric Observatory's Michelson Doppler Imager (SOHO/MDI, 1996–2011; Scherrer et al., 1995) and Solar Dynamics Observatory's Helioseismic and Magnetic Imager (SDO/HMI, 2010–present; Scherrer et al., 2012) space-borne synoptic magnetogram programs have

provided continuous full-disk observations from outside the Earth's atmosphere. The VSM and HMI instruments produce both LOS and vector full-disk magnetograms but, for reasons of sensitivity discussed by e.g. Petrie (2022), this paper focuses on LOS magnetograms. In particular, this paper will apply the LOS magnetograms products from the NSO's KPVT and SOLIS magnetographs (1974–2017), the WSO (1976–present), and the GONG network (2006–present).

Global coronal and heliospheric fields are usually studied using full-surface maps for the solar photospheric magnetic flux. Traditionally, since the 1960s, these “synoptic” maps have been built using a solar rotation's worth (a Carrington rotation or CR, ≈ 27.2753 days as observed from (near) Earth) of full-disk measurements for the line-of-sight (LOS) field component B_l . From these LOS data the radial field component B_r is estimated assuming that the photospheric vector field is mostly radial to a good approximation (Svalgaard et al., 1978; Wang & Sheeley, 1992; Petrie & Patrikeeva, 2009) by dividing through by the cosine of the heliocentric angle ρ between the local photospheric normal and the LOS, i.e. $B_r = B_l / \cos(\rho)$. These radial field data are then remapped to heliographic coordinates [longitude, sine(latitude)] and merged together to form a full-surface map for the radial magnetic field. In some cases with high-cadence observations, only data observed close to the central meridian are used in this process, but for the NSO maps studied here the merging takes the form of a weighted average, with the highest weighting given to observations closest to the central meridian.

This averaging process covers all heliographic locations observed during the given rotation. However, because of the tilt angle $B_0 \approx 7.25^\circ$ between the Earth's ecliptic plane and the solar rotation axis, we cannot observe both polar regions during a single rotation from (near) Earth. The north/south solar pole is tilted towards us during September/March of each year, the optimal time to observe this polar field. Each pole is unobservable from (near) Earth for about 6 months each year and is difficult to observe well generally. Satellite missions departing from the Sun-Earth line could alter this situation, but among such existing missions, only Solar Orbiter carries a magnetograph. Solar Orbiter's departure from the ecliptic plane to heliographic latitudes as high as 35° during the late phase of the mission, will help future studies of the solar polar field. However, for a long-term historical study like this one we are confined to observations taken from the Earth's vantage point.

The traditional synoptic map construction techniques involve collecting observations taken at different times throughout a solar rotation and merging observations that differ in age by up to about four weeks. The resulting maps are therefore referred to as “diachronic” maps. Rather than representing a snapshot of the full-surface magnetic flux distribution at a single moment, diachronic maps record the flux distribution around the central meridian over a full rotation. Full-surface single-moment snapshots are available instead in the form of “synchronic” maps which are provided by numerical flux-transport models (Schrijver & De Rosa, 2003; Arge et al., 2010; Upton & Hathaway, 2014). Such snapshots are currently produced by ingesting LOS field observations for the frontside as observed from (near) Earth and modeling unobserved flux transport by canonical near-surface flow patterns (supergranular diffusion, differential rotation, meridional flow), and the resulting maps

more appropriate as lower-boundary data for coronal and heliospheric models for specific times. However, traditional diachronic maps retain value in providing rotation-averaged representations of the global solar field for historical projects like this one.

Models of the global coronal magnetic field are available with a range of degrees of sophistication, from the simplest potential-field models such as the widely used PFSS model (Altschuler & Newkirk, 1969; Schatten et al., 1969) through linear and nonlinear force-free and magnetohydrostatic modeling to sophisticated and expensive radiative magnetohydrodynamic modeling (Wiegmann et al., 2017). The PFSS model and other models based on it such as the standard Wang–Sheeley–Arge solar wind model (Arge & Pizzo, 2000) may be implemented based on spherical Fourier expansions whose longitude- and colatitude-dependence are represented by spherical harmonic functions. When the most basic potential-field model is implemented this way it represents the coronal magnetic field as a sum of magnetic multipoles, making it especially useful for analyzing the basic properties of the evolving global coronal field, such as the dipole strength and tilt, the quadrupole strength, etc., which can give us a condensed overview of global coronal behavior over multiple solar activity cycles and hundreds of solar rotations. We will adopt this coronal magnetic field modeling approach here, but first, we will prepare a description of the global photospheric magnetic field.

2 Global photospheric flux transport and polar fields

Figure 1 shows a time-latitude “butterfly” diagram of the radial magnetic field for KPVT and SOLIS data. This plot is adapted from Petrie (2023), based on the original version in Petrie (2012), and derived from KPVT 512-channel and Spectro-Magnetograph and SOLIS/VSM LOS magnetograms. Together the KPVT and SOLIS data span nearly four solar cycles 21–24 (1974–2017). The magnetic flux transport patterns in Figure 1 were described and analyzed by (Petrie, 2023), including the signatures of AR emergence, decay, and dispersion by supergranular diffusion at a typical rate $\eta = 600 \text{ km}^2 \text{ s}^{-1}$, and transport to the poles by the canonical near-surface flows. One major purpose of showing Figure 1 here is to contrast the relatively high strength and hemispheric symmetry of cycles 21 and 22 with the weaker, more north-south asymmetric patterns of cycles 23 and 24. Whereas the north and south polar field reversals tended to occur relatively quickly and straightforwardly during cycles 21 and 22, at roughly the same time and speed of change, the cycle 23 and 24 polar field reversals were both noteworthy for the major differences between the north and south polar field changes. the south polar field reversed much more slowly than the north during cycle 23, and vice versa during cycle 24.

Figure 1 helps to identify the timing of this fundamental change of behavior from approximately symmetric to asymmetric during the declining phase of cycle 23, when the plumes of decayed AR flux (the oblique flux patterns between $\approx \pm 40^\circ$ and $\pm 60^\circ$ latitude became visibly much weaker and of more mixed magnetic polarity. Petrie (2012) showed quantitatively that the flux plumes in this latitude range became much weaker shortly

after the year 2000, and the polar field changes (the numerical polar field time-derivatives) followed this behavior in becoming much smaller and more gradual after this time compared to before (see also the polar flux time-derivatives in, Petrie, 2023).

Petrie (2012) also connected these patterns to a change in Joy’s law tilt (Hale et al., 1919) of the bipolar active regions, referring to the empirical law whereby the leading sunspot polarity lies preferentially closer to the equator than the trailing sunspot polarity in each hemisphere, where the leading and trailing sunspot polarities are defined by Hale’s law: the leading sunspots of the bipolar pairs in each hemisphere during each sunspot cycle generally have the same magnetic polarity, and this polarity is of opposite sign in the two hemispheres and alternates each cycle in each hemisphere. Petrie (2012) quantified the effect of Joy’s law tilts of ARs over several cycles by analyzing all ARs’ positive and negative magnetic flux latitude centroids in each hemisphere, and showing that the mean positive and negative centroids became much closer together in each hemisphere during cycle 23 compared to cycles 21 and 22. The high-latitude fields between $\approx \pm 40^\circ$ and $\pm 60^\circ$ latitude were well correlated to the product of the AR magnetic flux and the positive and negative AR flux latitudinal centroid separation (representing the Joy’s law tilt in each hemisphere), demonstrating the dependence of high-latitude field changes on not only activity cycle amplitude but also the Joy’s law tilt of the active regions (Petrie, 2012). Because the standard Babcock–Leighton flux transport model (Babcock, 1961; Leighton, 1964, 1969) relies on the ARs’ Joy’s law tilt to have a significant bias, such that the near-surface flows send predominantly trailing-polarity flux poleward and leading-polarity flux equatorward (referring to the leading and trailing sunspot polarities in each hemisphere defined by Hale’s polarity law), this convergence of the positive and negative AR flux centroids in each hemisphere diminished the efficiency of this mechanism, resulting in the weaker, more mixed-polarity poleward flux and the smaller, more gradual polar field changes. A mixture of ARs adhering to and violating Joy’s law (e.g. Whitbread et al., 2018) can produce converging positive and negative AR flux latitudinal centroids. The poleward plumes in Figure 1 are indeed clearly much stronger and of greater polarity bias during cycles 21 and 22 compared to cycles 23 and 24: the high latitudes are dominated by a smaller number of large, strong plumes of predominantly trailing polarity in each hemisphere during cycles 21 and 22, whereas the cycle 23 and 24 poleward plumes, especially in the south during cycle 23 and the north during cycle 24, are smaller, weaker, and more numerous, the polarity balance has much less bias, and the competition between the polarities is more contested.

That these strong, polarity-biased poleward flux surges of cycles 21 and 22 results in swift and decisive polar field changes is confirmed in Figure 2, which shows polar flux/field against time for KPVT/SOLIS and GONG (top) and WSO (bottom). The WSO field data represent the LOS component through a single $3'$ polar pixel, whereas the curves in the top panel of Figure 2 represent the polar (here poleward of $\pm 60^\circ$) radial flux and mean field. The curves in Figure 2 feature large, decisive polar field changes during cycle 21 (around 1980) and 22 (around 1990), and also a steep change during the rise of cycle 23 (before 2001), whereas from the declining phase of cycle 23 onwards the changes are qualitatively smaller and more gradual, and feature multiple polarity reversals. (The polar field

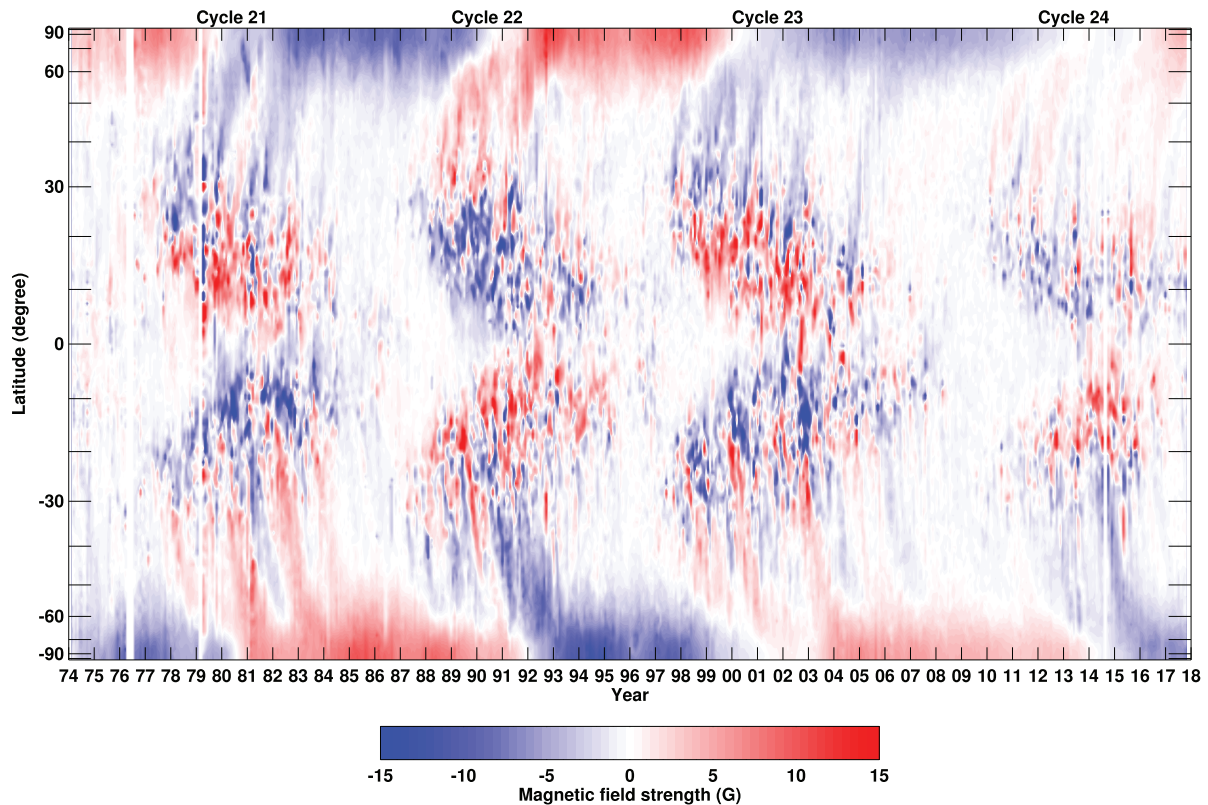


Figure 1. Time-latitude “butterfly” diagram of radial magnetic field for KPVT and SOLIS data. Adapted from Petrie (2023).

and flux derivatives shown in Petrie (2012) and Petrie (2023) also demonstrate this.) Note also the similarity in amplitude, slope, and zero-crossings of the north and south curves for cycles 21 and 22; apart from the slight kink in the south polar field curve near zero in 1990, these cycle 21 and 22 reversals were close to being north-south symmetric. For cycles 23 and 24, however, the north and south polar curves differ greatly, with the south polar field reversing much more slowly and equivocally than the north during cycle 23 and vice versa during cycle 24, consistent with Figure 1.

For a closer look at more recent developments, Figure 3 shows GONG “butterfly” diagrams of the radial magnetic field in the top panel accompanied by the polar flux plotted against time in the bottom panel. So far, cycle 25 has been more north-south symmetric in general than cycle 24: Figure 3 (top) shows that the southern hemispheric activity briefly led the north at the onset of the cycle (see also the sunspot number²), but within a year the north had balanced the south. At the time of writing, both poles are weakening relatively quickly, the north currently at a faster rate than the south. Indeed, according to the WSO and GONG data, the net flux at both poles subsequently weakened relatively quickly and, at the time of writing, the overall polarity has reversed in each polar region. The WSO curves lead the GONG curves in Figure 2 because the WSO data derive from the most poleward 3' pixel covering each pole, which (1) includes data down to $\pm 55^\circ$ latitude; (2) is weighted by the limb-darkened intensity profile towards the lowest latitudes covered by this pixel; and,

of course, (3) the polar field reversal progresses from lower to higher latitudes such that the lower-latitude regions reverse polarity earlier. Nevertheless, there is qualitative agreement between the WSO and GONG data as to the polarity reversal that has recently occurred at both poles, so far more symmetrically than the cycle 23 and 24 polar reversals.

3 Global coronal field and magnetic multipoles

The simplest way to represent the coronal response to the above photospheric flux emergence and transport patterns is to model the global coronal field with a PFSS model (Altschuler & Newkirk, 1969, Schatten et al., 1969). The inner boundary data for the model are provided by full-surface synoptic magnetograms for the radial field component B_r . Unobserved polar fields are represented in the maps by interpolating across the polar data gap using a low-degree polynomial surface fit in the case of NSO maps (KPVT, SOLIS, and GONG), and a $\cos^n(\theta)$ function of colatitude θ with $n = 8 \pm 1$ in the case of WSO (Svalgaard et al., 1978). The polar field data in the KPVT/SOLIS and GONG synoptic maps are also adjusted using the time-latitude polar data shown in Figures 1 and 3 to improve temporal continuity and eliminate annual B_0 -angle artifacts, following Petrie (2013).

The PFSS model outer boundary is set at the height where the magnetic field is believed to become dominated by the thermal pressure and inertial force of the expanding solar wind,

² <https://www.sidc.be/SILSO/home>.

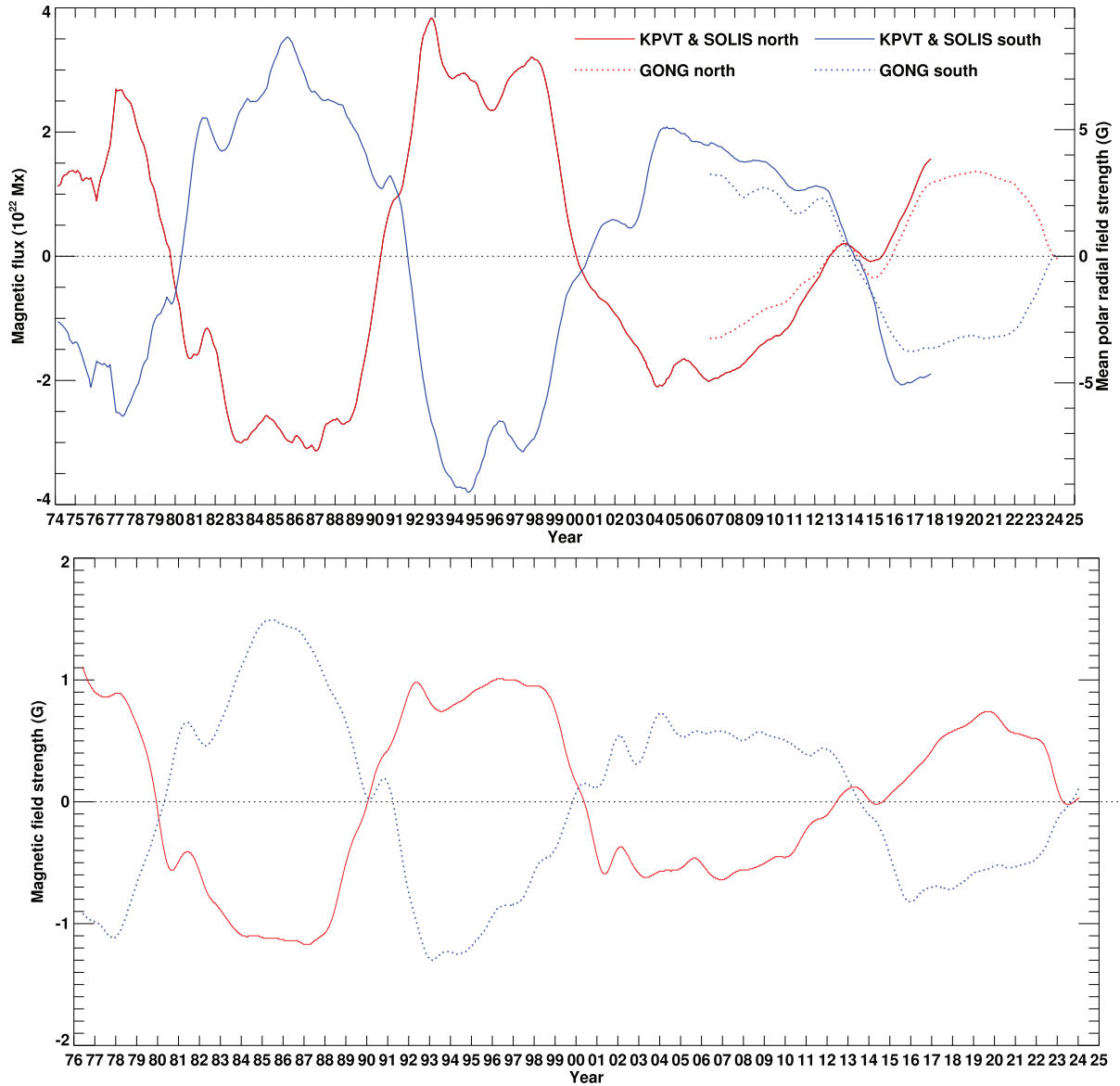


Figure 2. In the top panel, adapted and updated from Petrie (2023), the polar magnetic flux is plotted against time for KPVT and SOLIS (solid lines), and GONG (dotted lines) data. Here the polar region is defined as poleward of $\pm 60^\circ$, and the radial flux is plotted, with the axis to the right indicating the mean polar radial field strength. In the bottom panel, updated from Petrie (2013), the mean LOS field is plotted for Wilcox data.

beyond which height a force-free model such as the PFSS model is not applicable. At this height, the field is forced to be radial in the PFSS model, achieved by setting the potential function to a constant value everywhere on the outer boundary, modeling the effect of electric current sources associated with radial field expansion by the solar wind. The outer boundary surface is therefore called the source surface. Here we adopt the standard outer-boundary radius R_{SS} to be $R_{SS} = 2.5R_\odot$.

One key advantage of potential-field solutions is that they can be decomposed into multipole components based on spherical harmonics. This decomposition allows us to summarize the salient features of the global coronal field structure over long timescales in a simple and physically intuitive way by revealing which spatial scales and (anti)symmetries are dominant during each phase of each solar cycle. Spherical harmonics

are summarized and visualized in many textbooks and popular websites³.

The PFSS solutions are constructed as described briefly by Petrie (2013) and more fully by Hoeksema (1984). The principal index n is the total number of circles of nodes on the photosphere, and the secondary index m is the number of those nodal circles that pass through the pole. The lowest-order multipoles, i.e. those with lowest n values, correspond to the largest length scales, and components with $m = 0$ are axisymmetric. The $n = 0$ monopole component is ignored in the analysis because it is unphysical. In synoptic this term is non-zero due to errors associated with unobserved fields and evolution.

³ E.g., https://en.wikipedia.org/wiki/Spherical_harmonics <https://mathworld.wolfram.com/SphericalHarmonic.html>.

In high-quality synoptic maps, keeping in mind the errors and limitations mentioned in Section 1, these errors are small enough for our purposes such that the monopoles can simply be subtracted from the maps.

To measure the comparative influence on the global coronal field structure of the different multipole contributions we follow these authors and compare the strengths of these multipoles at the outer-boundary radius $R_{SS} = 2.5R_{\odot}$. This is necessary because multipoles of different orders have different r -dependence. An n th-order multipole field strength falls off with radius as $1/r^{n+2}$, so the lowest-order multipoles such as the dipole falling off as $1/r^3$ and the quadrupole falling off as $1/r^4$, dominate the global coronal/heliospheric structure.

We describe the temporal evolution of several of the lowest-order ($n = 1, 2, 3, \dots, 9$) terms (dipole, quadrupole, octupole, etc.) using Figures 4–6. The odd- and even-ordered axisymmetric and non-axisymmetric orders are plotted separately for KPVT/SOLIS in Figure 4, WSO in Figure 5, and GONG in Figure 6. The higher-order multipoles follow the sunspot cycle, i.e. are strongest when solar activity is strongest, because they are perturbed by smaller length scales that are dominated by ARs. The non-axisymmetric orders also follow the sunspot cycle because ARs are the main driver of non-axisymmetric coronal structure. Large-scale axisymmetric structure is provided by the polar fields, so it is no surprise that the lowest-order axisymmetric multipoles respond to the polar fields, and are strongest when the polar fields are strongest. The axial multipole components that are most responsive to the polar field variations are the lowest-odd-order ones, the axial dipole, and octupole.

The lowest-even-order axial multipole, the axial quadrupole, has a more complicated relationship with the photospheric magnetic fields. Unlike the axial dipole and octupole, which have odd order and are therefore anti-symmetric about the equator, the axial quadrupole has even order and is symmetric about the equator. Being non-zero around the equator, the axial quadrupole can respond to low-latitude AR flux, although the large spatial scale of the quadrupole makes its response to the bipolar ARs quite weak. On the other hand, having like-polarity polar fields, the axial quadrupole only responds to the Sun's polar fields when they depart significantly from their canonical state of having opposite polarity and approximately equal strength. Interpretation of the axial quadrupole can therefore be complicated, but when the north and south polar fields evolve with different amplitudes and rates of change, as occurred during cycles 23 and 24, the axial quadrupole is an especially important quantity to understand, as we will see in Section 4.

Figure 7 shows the axial (solid line) and equatorial (dotted line) dipole components as functions of time. The axial dipole is plotted including its sign. Its strength waxes and wanes with the polar fields' strength and its polarity follows the polarities of the north and south polar fields, being positive/negative whenever the north polar field is positive/negative and the south polar field is negative/positive. The equatorial dipole is the pythagorean sum of two orthogonal equatorial dipole components and is therefore non-negative. It has maximum strength when the low-latitude, active-region fields are strongest, i.e., during activity cycle maxima. The axial and equatorial dipole strengths therefore wax and wane in anti-phase. This is because of the nature of the Babcock-Leighton mechanism discussed in Section 2 whereby the polar fields change in response to magnetic activity via active-region decay and poleward flux transport.

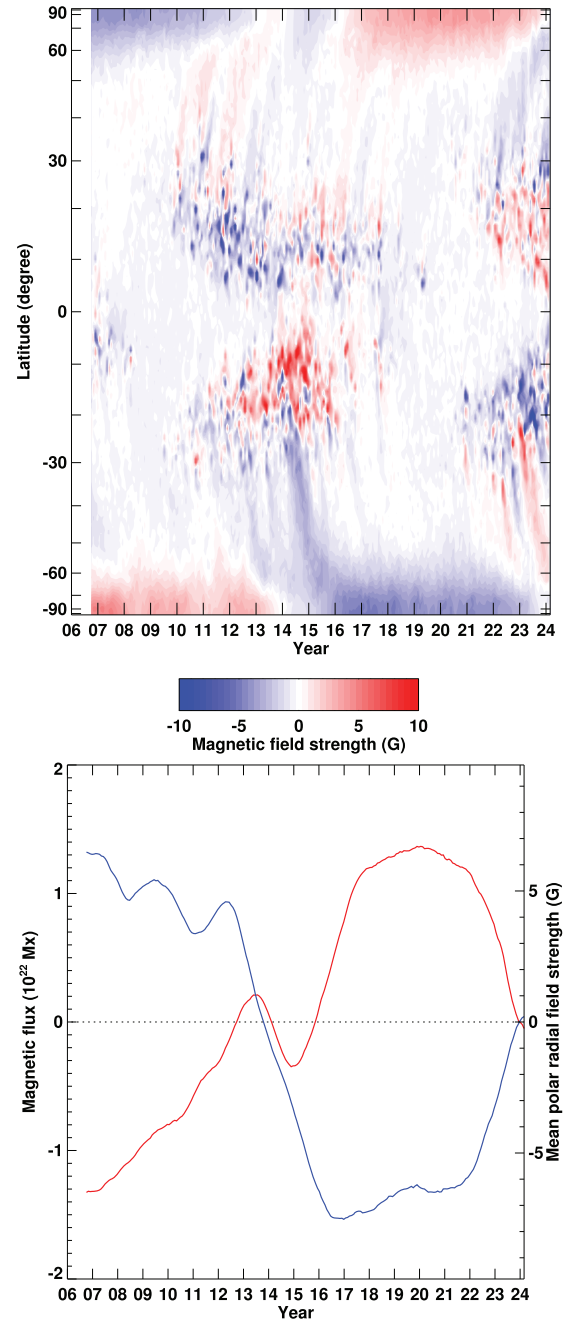


Figure 3. For GONG data a time-latitude “butterfly” diagram of radial magnetic field is shown in the top panel, and the polar flux plotted against time in the bottom panel. In the bottom plot, the polar region is defined as poleward of $\pm 60^\circ$, and the radial flux is plotted, with the axis to the right indicating the mean polar radial field strength. Adapted and updated from Petrie (2023).

In particular, it's because the polar fields decline to zero and reverse polarity during active phases of the cycle that activity maxima and polar field strength minima occur close in time.

The dipole tilt angle is plotted against time in Figure 8. This is the angular displacement of the vector formed by the axial and equatorial dipoles from Figure 7 with respect to the equatorial plane, and it takes values $\pm 90^\circ$ when the axial dipole is dominant with a positive/negative value, and 0° when the

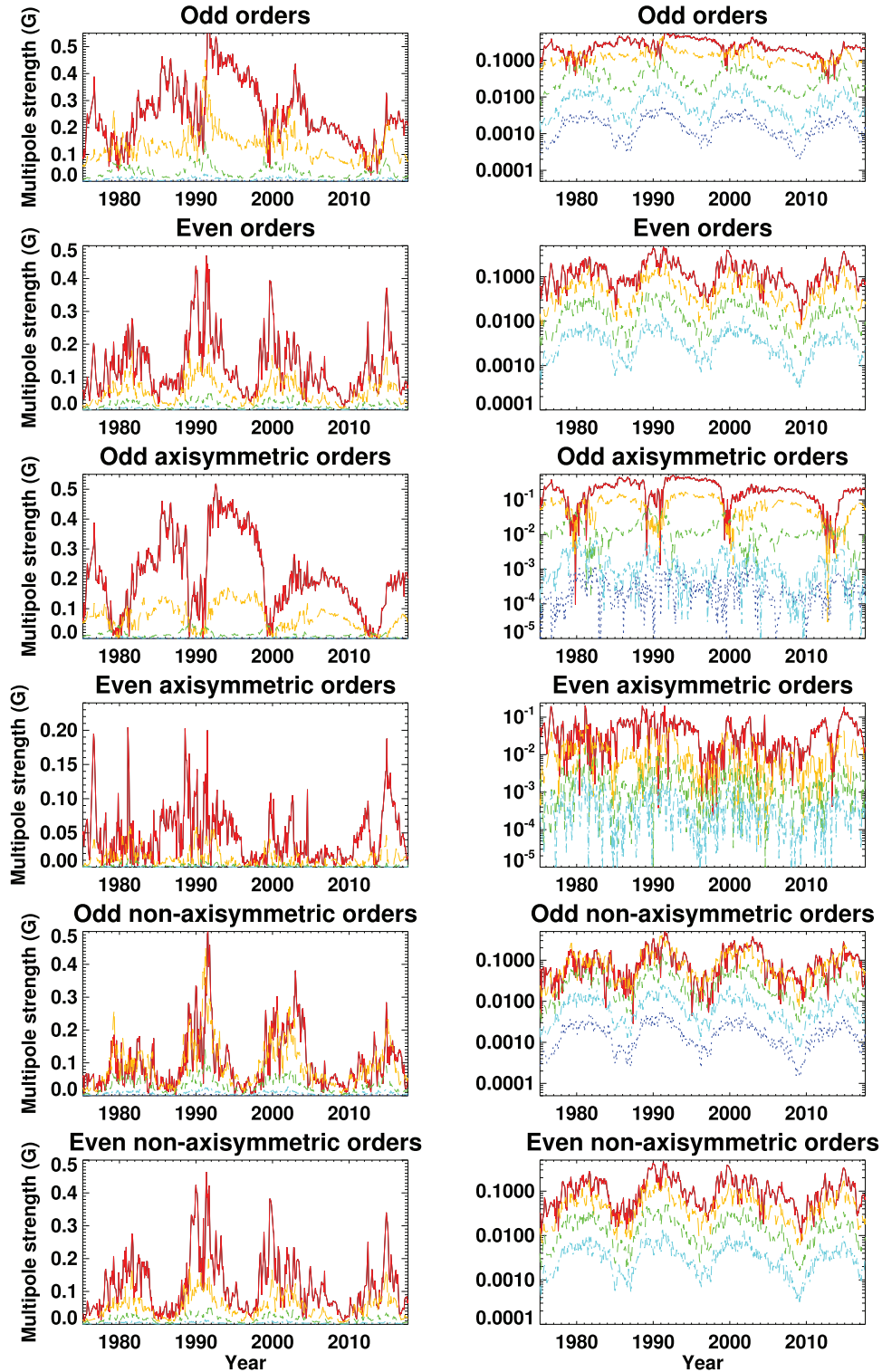


Figure 4. For KPVT and SOLIS data the first several orders of multipole components are plotted, showing the distinct cycle-dependent behavior of the even and odd, and axisymmetric and non-axisymmetric, orders in a systematic way, as indicated in the titles of the plots. The colors identify the numerous multipole components in question, with warm-to-cold colors denoting low-to-high orders. For odd orders, red, amber, green, cyan, and blue represent fields with $n = 1, 3, 5, 7, 9$, respectively. For even orders, red, amber, green, and cyan represent fields with $n = 2, 4, 6, 8$, respectively. The right column is the same as the left but scaled logarithmically to enhance the visibility of the signal in the higher-order components. Updated from [Petrie \(2013\)](#).

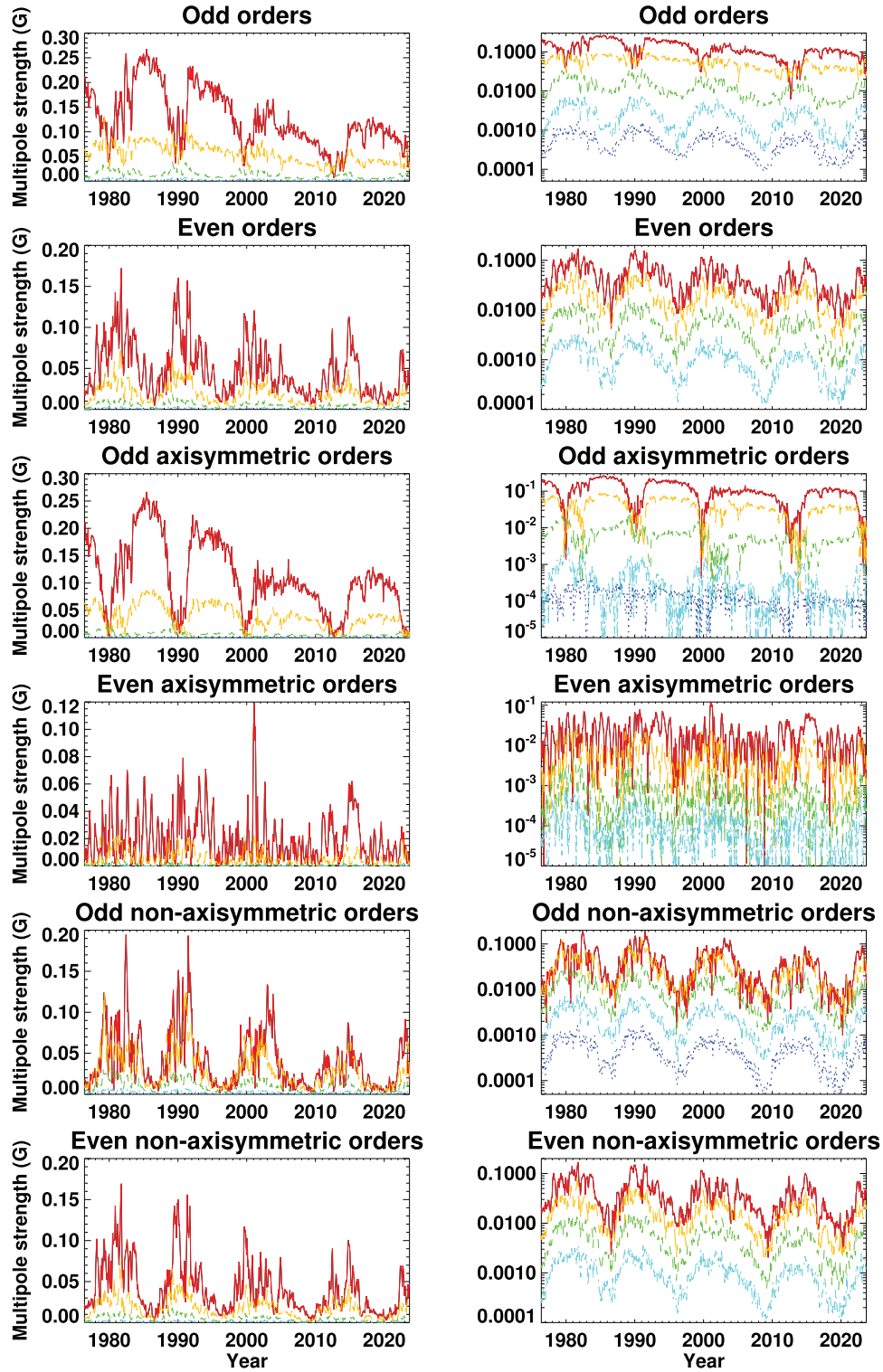


Figure 5. For WSO data the first several even- and odd-order multipole components are plotted, showing the distinct cycle-dependent behavior of the even and odd, and axisymmetric and non-axisymmetric, orders in a systematic way, as indicated in the titles of the plots. The colors identify the numerous multipole components in question, with warm-to-cold colors denoting low-to-high orders. For odd orders, red, amber, green, cyan, and blue represent fields with $n = 1, 3, 5, 7, 9$, respectively. For even orders, red, amber, green, and cyan represent fields with $n = 2, 4, 6, 8$, respectively. The right column is the same as the left but scaled logarithmically to enhance the visibility of the signal in the higher-order components. Updated from [Petrie \(2013\)](#).

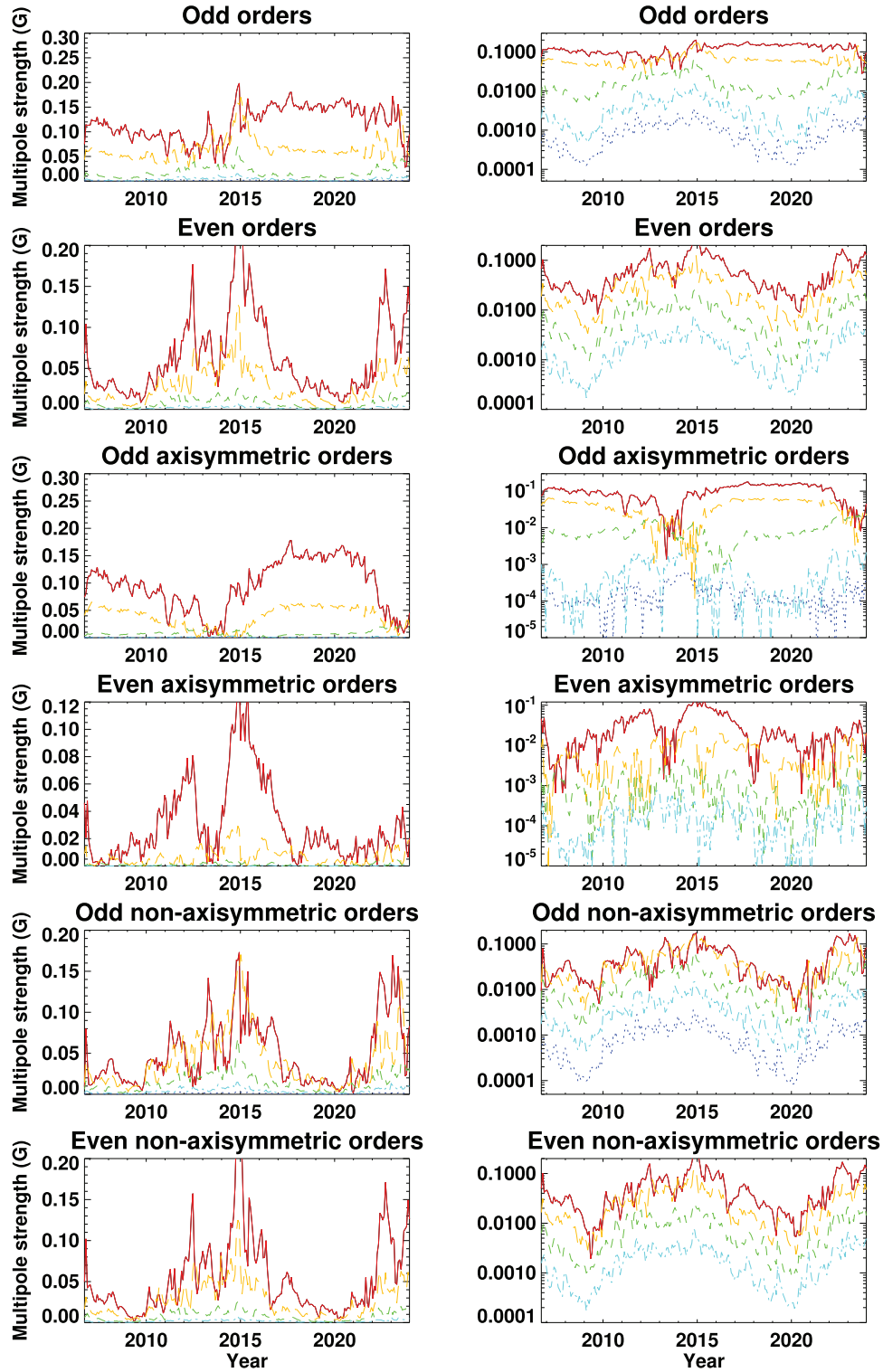


Figure 6. For GONG data the first several even- and odd-order multipole components are plotted, showing the distinct cycle-dependent behavior of the even and odd, and axisymmetric and non-axisymmetric, orders in a systematic way, as indicated in the titles of the plots. The colors identify the numerous multipole components in question, with warm-to-cold colors denoting low-to-high orders. For odd orders, red, amber, green, cyan, and blue represent fields with $n = 1, 3, 5, 7, 9$, respectively. For even orders, red, amber, green, and cyan represent fields with $n = 2, 4, 6, 8$, respectively. The right column is the same as the left but scaled logarithmically to enhance the visibility of the signal in the higher-order components.

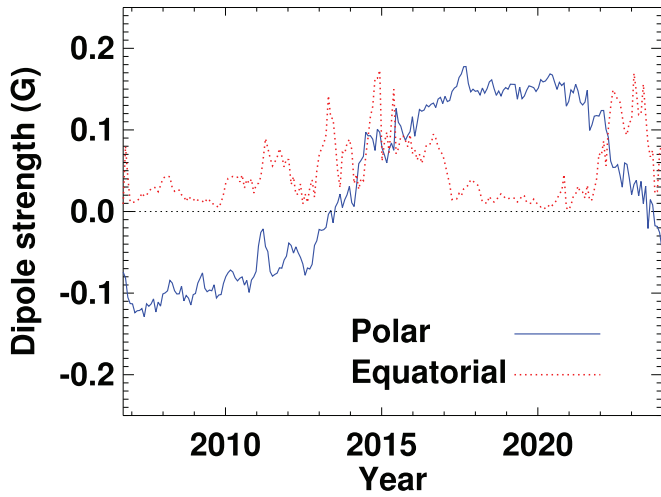
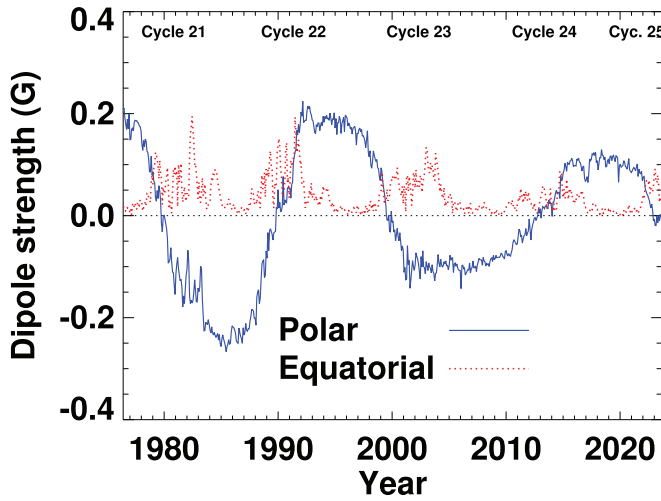
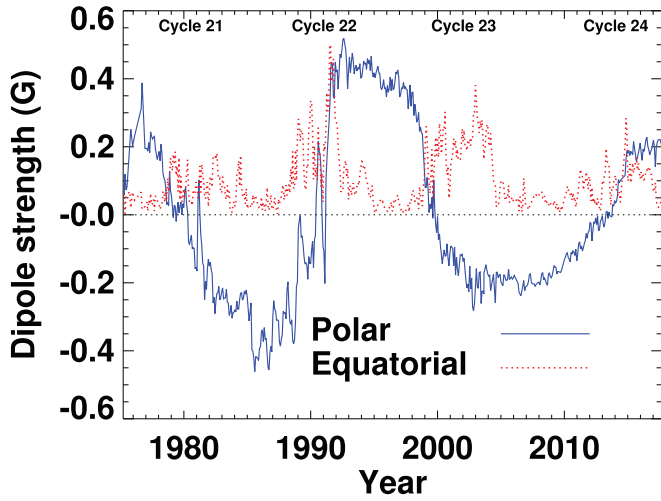


Figure 7. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the axial (blue solid lines) and equatorial (red dotted lines) dipole components are plotted against time. Adapted and updated from [Petrie \(2013\)](#).

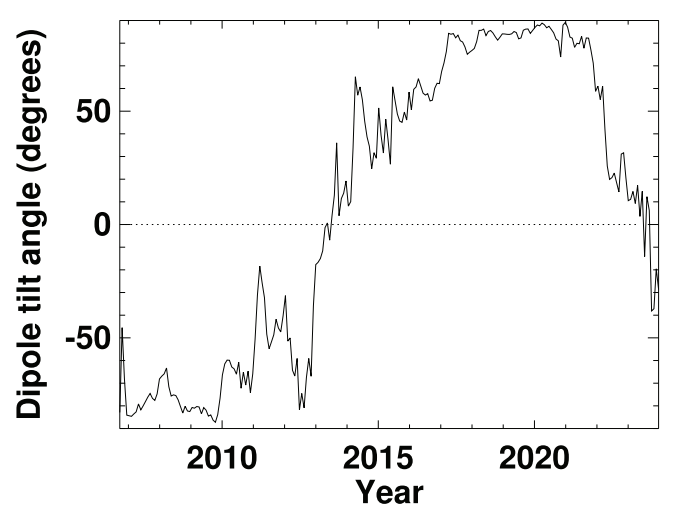
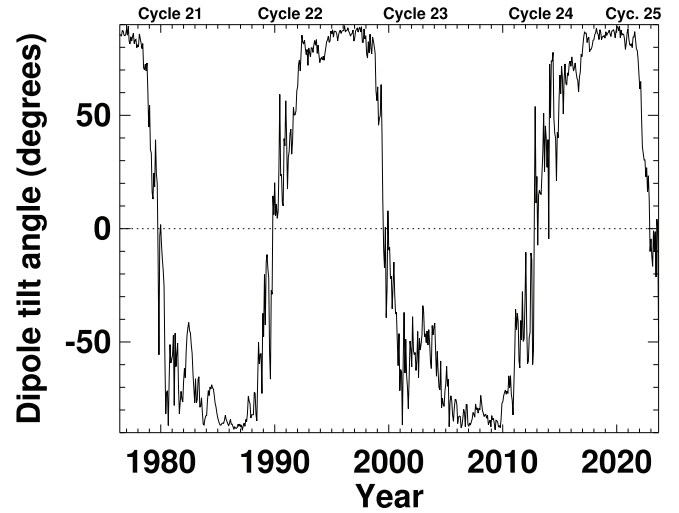
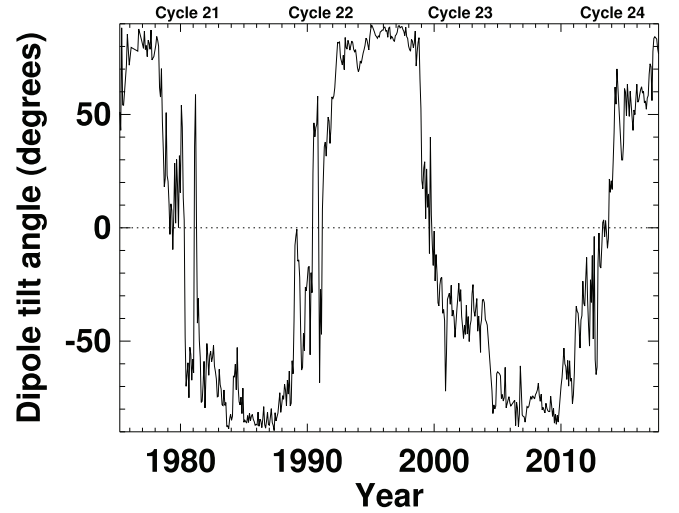


Figure 8. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the dipole tilt angle is plotted against time. Adapted and updated from [Petrie \(2013\)](#).

axial dipole is weak and the equatorial dipole is dominant. The anti-phasal waxing and waning of the axial and equatorial dipoles gives the dipole tilt its sinusoidal behavior.

The dipole tilt reversals appear less clear during cycle 21 and 23 than during cycle 22 and 24, with plateaux at around -60° during cycle 21 (1980–83) and around -50° during cycle 23 (2000–03), subsequently settling close to -90° in both cases. In contrast, the cycle 22 dipole tilt reversal (around 1990) converged straightforwardly to values close to 90° , albeit with a minor interruption of the south polar field trend in 1990 (see Fig. 2), associated with an isolated positive south-poleward surge at this time (see Fig. 1); and the cycle 24 dipole tilt reversal (2012–16) was also relatively simple, albeit convergence was slower during cycle 24 than during cycle 22 due to complications that we will discuss in Section 4.

The explanation for the cycle 21 dipole tilt plateau of 1980–83 is that both the north and south polar fields ceased to strengthen during this time: see the pause in the progress of the axial dipole during this time, and the simultaneous stalling of both polar fields in Figure 2. This development was due to major poleward surges of the decayed active-region flux of leading sunspot polarity during this time in both hemispheres, interrupting the dominant trailing-polarity surges, as shown in Figure 1.

As described in Section 2, during active phases of the solar cycle the emergence and decay of bipolar active regions with Joy’s law tilt results in much mutual cancellation of the two hemispheres’ magnetic flux of leading sunspot polarity, leaving the trailing-polarity flux in each hemisphere to travel poleward and change the polar field. Solar activity therefore tends to change a given polar field according to the trailing sunspot polarity in its hemisphere. Sometimes, however, significant quantities of leading-polarity flux reach the pole either because Joy’s law for magnetic bipole tilt angles is not strictly adhered to by all active regions, or because the leading-polarity flux does not cancel with its counterpart in the opposite hemisphere for another reason, e.g., a pause in flux emergence. The lack of significant change in Joy’s law tilt bias in either hemisphere during this time (Petrie, 2012) favors the latter explanation.

The cycle 23 dipole tilt plateau of 2000–03 has a clearer explanation, and it appears to have had more profound, longer-term consequences for the global solar field. Whereas during cycle 21 the polar fields’ progress was merely interrupted for a year or so by the poleward transport of leading-polarity flux, during cycle 23 the axial dipole simply ceased to develop significantly beyond 2001 despite several more years of significant activity. Thus the dipole tilt stalled at around -50° from 2001 until the activity finally died down in the mid-2000s, when the still-weak polar fields could finally produce a dominant axial dipole. Petrie (2012) showed that the mean latitudinal separation of the centroids of the active regions’ positive and negative fluxes became statistically equivalent to zero during the last several years of cycle 23, i.e. the Joy’s law tilt essential to polar field change effectively vanished during this time, so that the poleward surges lost their overall trailing-flux bias and thus the polar fields ceased to develop in both hemispheres. This did not occur during the other cycles covered by these data sets, where the positive and negative AR flux centroid separation persisted until the cycle declined to minimum activity levels. Cycle 23’s polar field growth therefore slowed and stalled

several years before activity ceased, unlike the other cycles covered here. The consequences of the resulting weak cycle 23 polar fields are widespread across global coronal and heliospheric physics (Petrie, 2015), including the strength of the IMF (Smith & Balogh, 2008) and the physical properties and geoeffectiveness of CMEs (Gopalswamy et al., 2014, 2015).

4 Hemispheric asymmetry and the axial quadrupole

Hemispheric asymmetries in global solar field structure have long been of interest. Using ≈ 40 years of hourly IMF data from the NASA OMNI database, Mursula & Hiltula (2003) found a systematic dominance of IMF sectors sharing the magnetic polarity with the northern heliographic hemisphere, and concluded that the heliospheric current sheet (HCS) is on average shifted or coned southwards like the high flaring skirt of a “bashful ballerina”, at least during solar activity minima. Virtanen & Mursula (2016) modeled global long-term coronal field evolution using PFSS models based on synoptic magnetograms from six magnetographs together spanning ≈ 40 years, and found general agreement regarding the southward shift of the heliospheric current sheet in the declining to minimum phase of the solar cycle. The authors attributed this shift mainly to the axial quadrupole term during solar cycles 20–22 and the rise of cycle 24, and a less persistent shift during cycle 23 mainly to higher-order harmonics.

Wang & Robbrecht (2011) showed using kinematic photospheric flux-transport and coronal PFSS models that the southward HCS displacement can be caused by a combination of the Joy’s law tilt and hemispheric asymmetry of bipolar ARs, consistent with the observed hemispheric asymmetry in the sunspot number, with stronger activity in the southern/ northern hemisphere during the declining/rising phase of cycles 20–23. This hemispheric asymmetry causes an axisymmetric quadrupole field in the coronal model, with equatorial magnetic polarity sharing the sign of the leading-polarity flux in the dominant hemisphere. Wang & Robbrecht (2011) thus explained why the polarity of the IMF tended to match that of the north polar field both before and after polar field reversal during the last four cycles, again consistent with a southward shift of the HCS.

Evidence therefore exists that hemispheric magnetic field asymmetries are persistent, significant, and have global consequences in the heliosphere, in particular for the IMF at Earth. These asymmetries have been connected to hemispheric asymmetries in AR flux emergence. In this section, we contrast the even- and odd-ordered axial multipoles with particular attention to their sign, strength, and relationship to both ARs and polar fields.

Figure 9 shows the first three axisymmetric odd multipole orders, including their polarities, as functions of time. The axial dipole plotted here is repeated from Figure 7. The axial octupole and higher odd orders generally have the same sign as the axial dipole at each phase of the solar cycle, driven by the polarities and strengths of the polar fields. However, the higher a multipole’s order the lower its strength because the greater the fall-off of its field strength with height recall from Section 3 that

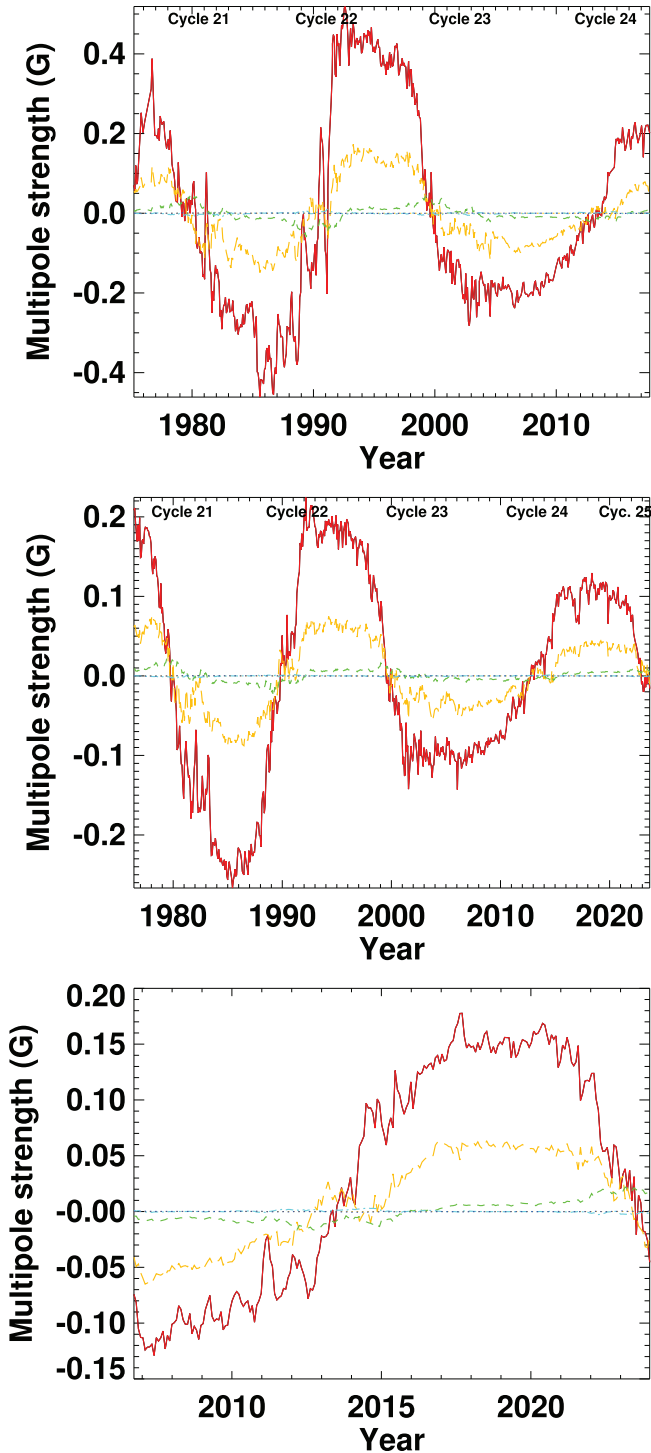


Figure 9. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the signed axial odd multipole strengths are plotted against time. Red, amber, and green represent fields with $n = 1, 3, 5$, respectively.

we compare the strengths of these multipoles at the outer-boundary radius $R_{SS} = 2.5R_{\odot}$. There is also a time lag between the dipole and the higher orders: the octupole's polarity reversal lagged the dipole's by a couple of years during cycle 24 (2012–2014), and the 5th-order axial multipole (dotriacontapole) lags

the dipole and octupole around the time of every polar reversal shown in Figure 2. This is because of the nature of polar field reversal which begins with poleward transport of magnetic flux from lower latitudes as seen in Figure 1 (see also the polar plots in Petrie (2022) for a polar perspective). The lower-order multipoles, being sensitive to fields on larger spatial scales, are therefore perturbed by poleward surges of flux before the higher-order multipoles can respond to them.

Figure 10 shows the first three axisymmetric even multipole orders, including their signs, as functions of time. These even axial orders are generally significantly weaker than their odd-order counterparts because, being north-south symmetric, they have the same sign at the two poles, whereas the north and south polar fields are generally of opposite magnetic polarity. Thus, whereas the odd axial orders respond more directly to the polar field strengths, these even orders generally represent residual north-south asymmetries in the polar field strengths, which tend to occur most significantly during polar field reversal: if the poles reverse polarity at significantly different times or rates then a polar field asymmetry arises that the odd axial orders cannot capture. It is therefore during asymmetric polar field reversals that the even axial orders play the most significant role.

A clear example of this is the cycle 24 reversal when the north polar field began to reverse well before the south polar field did, and yet also completed its reversal later, creating a series of polar asymmetries and axial quadrupolar fields as follows. Referring to Figure 2 along with Figures 9 and 10: when the north polar field began to weaken in 2010, the axial dipole also weakened and the axial quadrupole became positive because of the positive polar bias associated with the still-strong south polar field. Then the north polar field stalled close to zero during 2013–15, and during this same period, the south polar field swiftly reversed from positive to negative polarity. With this south polar field reversal the axial dipole also reversed polarity from negative to positive, and the axial quadrupole reversed from positive to negative, the dominant polar field now being negative. Both the dipole and quadrupole reversals were therefore straightforward consequences of the south polar reversal taking place while the north polar field remained weak throughout, and they occurred close in time to the south polar reversal in 2013. The north polar field remained weak until after the south polar field reversal was completed in 2015. The axial quadrupole was therefore strong and negative for several years between 2013 and 2016, and then became weak during the decline and minimum of cycle 24.

According to Figure 2, the cycle 22 polar field reversal was also north-south asymmetric: both north and south polar fields declined swiftly towards zero in 1990 but, whereas the north polar field continued relatively straightforwardly through zero into positive values, the south polar field stalled near zero for a year or so. Figure 9 shows that the axial dipole straightforwardly reversed polarity from negative to positive during 1990, and Figure 10 shows that the axial quadrupole became positive due to the new polar asymmetry. The south polar field then reversed decisively in 1991, and then proceeded to strengthen quickly, outweighing the north from 1992 for a few years, causing the axial quadrupole to become negative and strong between 1992 and the mid-1990s, whereupon the poles became more evenly balanced and the axial quadrupole became weak again.

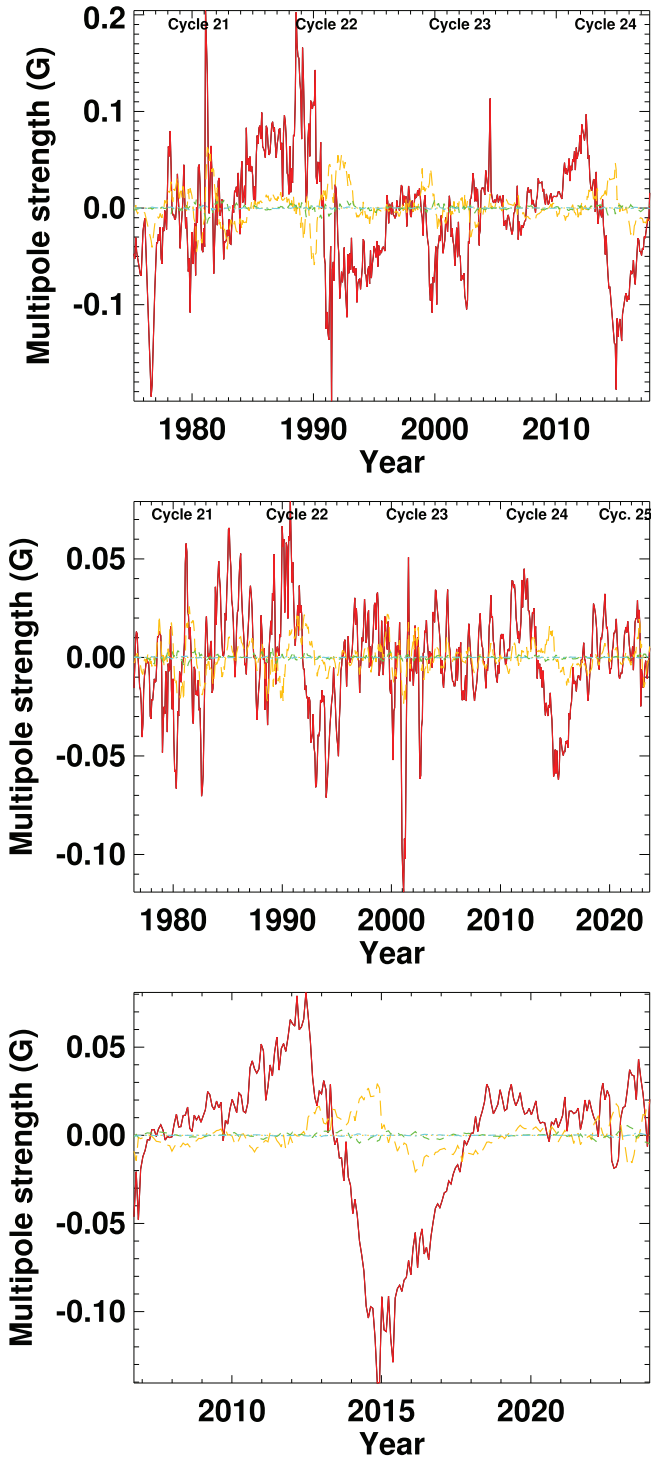


Figure 10. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the signed axial even multipole strengths are plotted against time. Red, amber, and green represent fields with $n = 2, 4, 6$, respectively.

Figure 11 shows the linear sum of all (even- and odd-order, solid line), odd-order (dotted line), and even-order (dashed line) axial components. These linear sums represent the combined strength of the respective axial components at the poles. Note that in Figures 4–8, different multipole components are

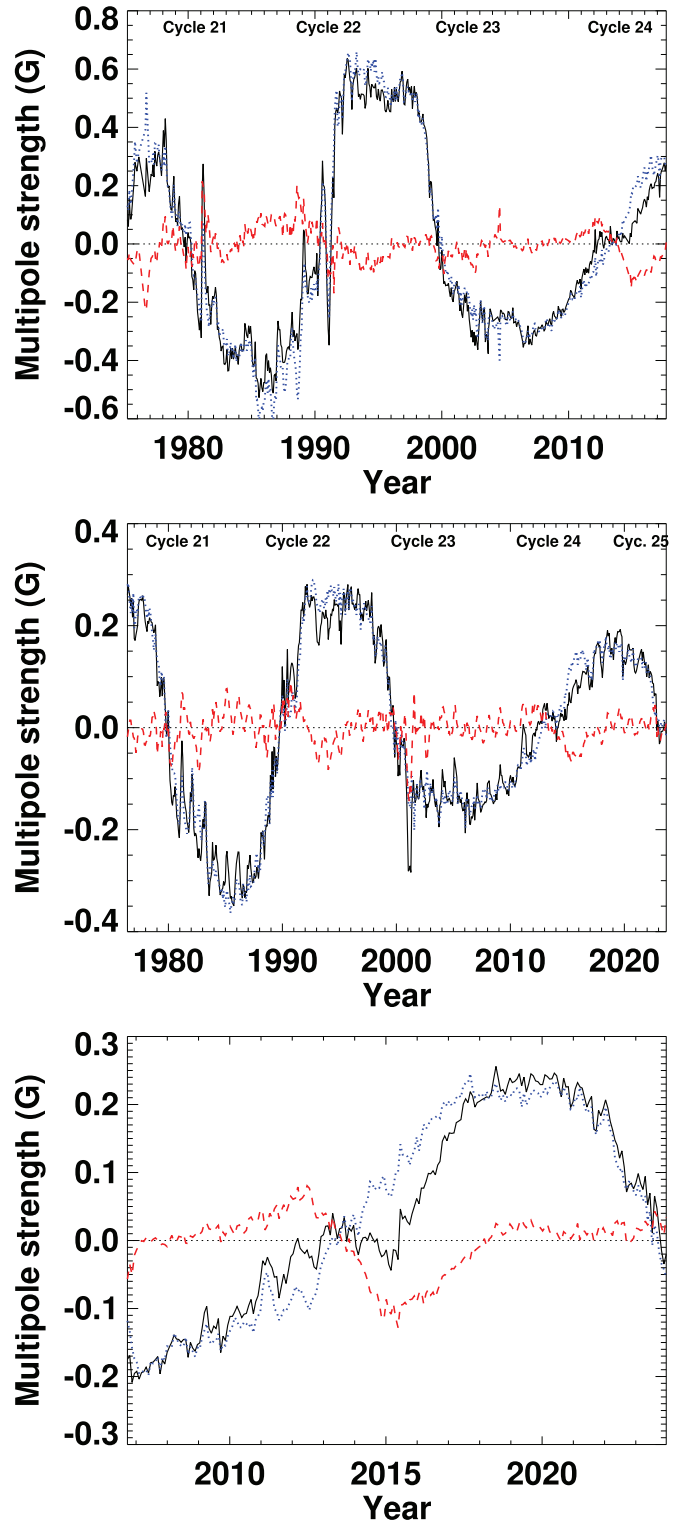


Figure 11. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the signed sum of all (black solid curves), odd-order (blue dotted curves) and even-order (red dashed curves) axial strengths are plotted against time.

combined in pythagorean sums because they form an orthogonal set (Hoeksema, 1984). Regarding the polar fields, however, one can combine axial components linearly to study

their cumulative contributions at the poles. The closeness of the solid line to the dotted line in Figure 11 confirms how much the axisymmetric coronal field is dominated (at the poles) by the odd axial components.

Note the prevalent negative correlation between the signed odd-order and even-order strengths in Figure 11. In each of the three data sets the odd-order and even-order strengths have opposite signs the majority of the time: 68% of the KPVT and SOLIS models, 55% of the WSO models, and 62% of the GONG models. We will discuss this negative correlation at the end of this section.

Figure 12 shows the same quantities as shown in Figure 11, but normalized by the combined axisymmetric multipole strength, i.e. the pythagorean sum of the individual axial multipole strengths (Hoeksma, 1984; Petrie, 2013). These normalized quantities can take values greater than 1 because linear sums can exceed pythagorean sums. The purpose of showing these normalized axial odd- and even-order multipole contributions is to demonstrate the significance of these components in terms of the overall strength of the full (axial) coronal field. Thus Figure 12 emphasizes how dominant the contribution of the odd-order (dotted line) axial multipoles almost always is to the full axial field (solid line) compared to the even-order (dashed line) multipoles' contribution.

Note, however, the exceptional behavior with regard to this rule during the cycle 24 polar field reversal (2012–2016), in contrast to the previous three polar reversals shown in Figure 12. Whereas each solid line exhibits an abrupt, stepwise reversal during each of cycles 21–23, the cycle 24 polar reversal was much more complex. For cycle 24 each solid line indicates a quick initial axial field reversal from a large negative value to a large positive value in 2012, but the full axial field subsequently changed to much smaller, near-zero values a year or so later, then gradually increased to larger positive values over the next few years until the polar reversal was complete. Both the odd- and even-order axial multipoles show behavior unique to cycle 24: the large positive and negative turns of the odd-order curves and the gradual recovery of both odd- and even-order curves, all of which causes the full axial field to behave in a more complex way during cycle 24 compared to the earlier cycles.

Recall that the axial quadrupole is north-south symmetric with the same polarity at the two poles and opposite polarity at the equator: the latitude-dependence is described by the associated Legendre polynomial $P_l^m(\cos \theta)$ which for the axial quadrupole is $P_2^0(x) = (3x^2 - 1)/2$. The axial quadrupole can therefore be perturbed by fields at high and/or low latitudes. To understand the dominant behavior of the axial quadrupole, we now discuss the relations between the axial quadrupole moment and the polar field evolution and activity patterns in turn, in more specific detail.

The cycle 24 axial quadrupole changes can be compared with the polar field changes, shown in Figures 2 and 3, as follows. The initial north polar field change began in 2012, from a strong negative value to a much smaller value, assisting the overall axial field reversal with a positive even-order contribution. However, when the south polar field then abruptly reversed from positive to negative, the even-order contribution became sharply negative and the full axial field took a much smaller

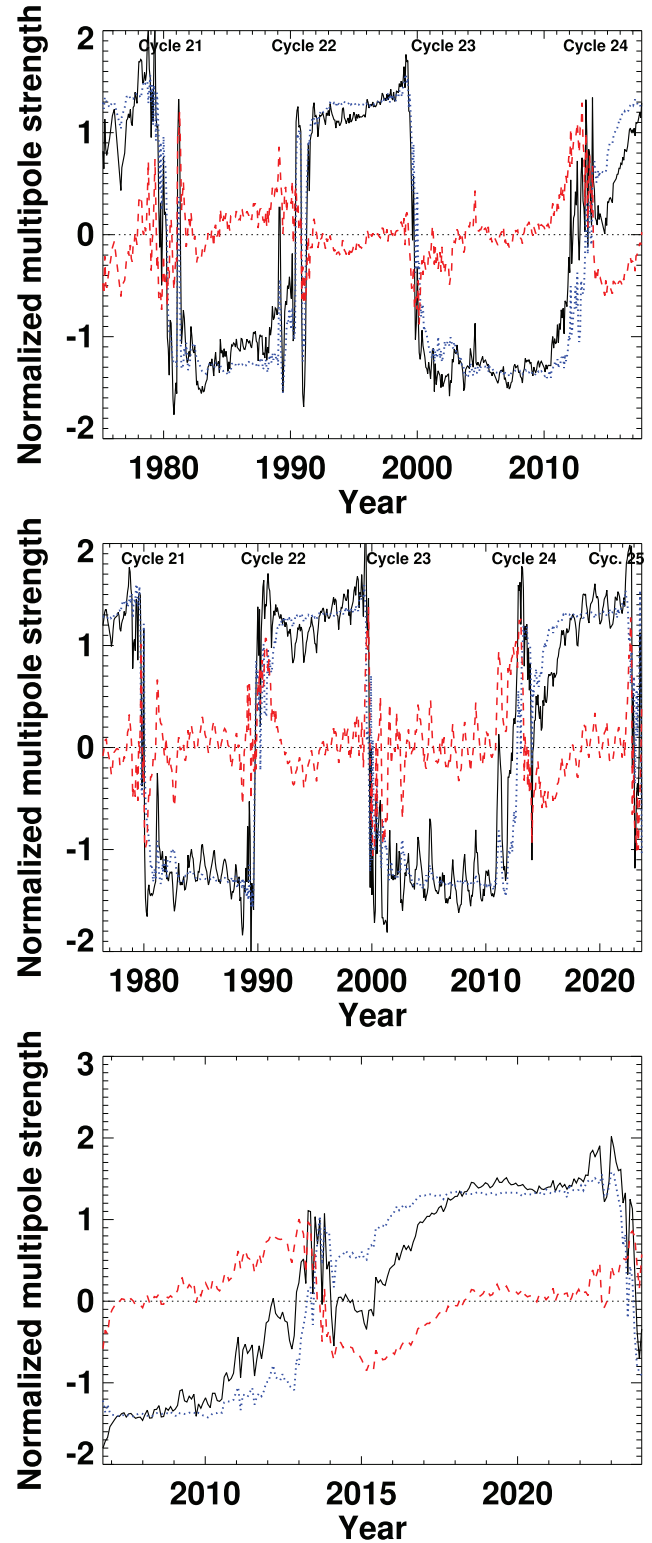


Figure 12. For KPVT and SOLIS (top), Wilcox (middle), and GONG (bottom) data the signed sum of all (black solid curves), odd-order (blue dotted curves), and even-order (red dashed curves) axial strengths are plotted against time as shown in Figure 11 but normalized by the combined axisymmetric multipole strength, i.e. the pythagorean sum of the individual axial multipole strengths.

value. As the north polar field finally completed its reversal the even-order contribution steadily shrank and the full axial field recovered its strong positive value. The significance of these patterns is unique to cycle 24, as Figure 12 demonstrates, because of both the size and duration of the polar asymmetry and the weakness of the polar fields during that cycle.

The cycle 24 axial quadrupole changes can also be compared with the AR flux emergence, shown in Figures 1 and 3, as follows. The initial activity of cycle 24 began in the north in 2010–2011, and had negative leading sunspot polarity dominating the low latitudes which, because the axial quadrupole mode has its negative peak at the equator, contributed towards a positive axial quadrupole during the rise of cycle 24. Then, the southern hemisphere became much more active than the northern, and its positive leading sunspot polarity dominated the low latitudes, assisting in turning the axial quadrupole negative. The reign of the strong southern-hemispheric activity lasted only a couple of years, however, and was outlasted by the northern activity, whose negative leading sunspot polarity was left to give a positive axial quadrupole during the declining phase of cycle 24.

The polar contribution to the axial quadrupole is worth discussing further because of its direct links to the HCS structure and the radial IMF. Revisiting the southward HCS displacement discussed by Mursula & Hiltula (2003), Wang & Robbrecht (2011), and Virtanen & Mursula (2016), the areal dominance of one magnetic polarity over the other can be understood in terms of the interaction of the dipole and quadrupole moments as follows. Recall that if the axial quadrupole is dominated by the polar field asymmetry then its low-latitude response matches the polarity of the weaker polar field. If such a polar-driven axial quadrupole significantly contributes to the low latitudes then these latitudes have a polarity bias matching the weaker of the two poles. The HCS therefore tends to be displaced from the weaker pole towards the stronger pole. Since the total magnetic flux must balance, the magnetic flux matching the pole with higher flux density generally fills a smaller solid angle in the heliosphere than does the flux matching the weaker pole. Hence the HCS should generally shift or cone towards the stronger pole.

Returning to the prevalent negative correlation between the signed odd-order and even-order strengths in Figure 11, we can now see that this negative correlation is consistent with the general southward shift of the HCS found by Mursula & Hiltula (2003) in IMF data and by Virtanen & Mursula (2016) in PFSS modeling. The latitude-dependence of the spherical harmonics is described by associated Legendre polynomials $P_l^m(\cos\theta)$ which are $P_1^0(x) = x$ for the axial dipole and $P_2^0(x) = (3x^2 - 1)/2$ for the axial quadrupole. A positive axial dipole therefore has positive north pole, negative south pole, and zero radial field at the equator, whereas a positive axial quadrupole has a positive north and south poles and negative radial field at the equator. If the globally dominant odd- and even-order axial multipoles, the axial dipole and quadrupole, have opposite signs then their north polar fields have opposite signs, weakening their sum, their south polar fields have the same sign, strengthening their sum, and the sum of their low-latitude fields is defined by the quadrupole with polarity opposing the south pole.

In our scenario with a prevalent negative correlation between the signed odd-order and even-order strengths, it therefore follows that the south-polar field is generally stronger than the north-polar field, and the low-latitude field has polarity opposing the south pole, implying that the HCS is preferentially shifted south of the equator. Thus the behavior shown in Figures 11 and 12 is consistent with past results, but it is explained here as predominantly an effect of the polar fields on global coronal structure, where the dominant axial dipole and quadrupole moments, driven by the polar fields, determine the prevailing large-scale magnetic polarity bias at low latitudes, and thereby the HCS latitude displacement from the equator.

5 Effects of global solar field decrease and hemispheric asymmetry on the radial interplanetary field

5.1 The weakening solar and interplanetary field: the second activity peak of cycle 23

It is well known that the overall intensity of solar activity has declined over the last several cycles, including the strength of the global solar field. For example, Virtanen et al. (2020) showed using PFSS coronal field models and OMNI IMF data that the best agreement between the coronal magnetic field and the HMF observed at the Earth is achieved if the source surface radius, representing the effective coronal size, decreases in time, with an abrupt decrease in the late 1990s. Recall that Petrie (2012) and Petrie (2023) emphasized fundamental changes in the AR flux emergence patterns and consequences for the global solar field around the year 2000, when the cycle 23 polar fields had just reversed and subsequently ceased to strengthen. Section 3 of the present paper also mentioned this topic briefly. We discuss it more fully here.

The cycle 23 polar reversal is of particular interest because of the change in amplitude, hemispheric symmetry, and general complexity of the global magnetic field patterns after this polar reversal compared to before. The most fundamental change occurring over the 50-year span of the data set is the weakening of the global solar magnetic field over this period: in particular, the polar fields created during cycles 23 and 24 were much weaker than those resulting from cycles 21 and 22: the polar fields, both north and south, have been only about 60% as strong since the cycle 23 polarity reversal compared to before (Petrie, 2015). Meanwhile, there was a 30%–40% drop in IMF between the cycle 22 and cycle 23 solar minima (Smith & Balogh, 2008). Figure 13 (top panel) shows a comparison between the global solar field strength and the unsigned radial IMF as functions of time: the mean absolute (unsigned) IMF from the OMNI database is plotted against time with 13-rotation smoothing, with the WSO axial multipole strength, the non-axisymmetric multipole strength, and the combined strength of all multipoles overplotted. WSO data are used for this comparison because only minor instrumental changes have taken place at this observatory over nearly fifty years, giving this data set unique long-term consistency as far as the field strength is concerned.

The radial IMF curve and the three WSO curves all trend generally downward over the ≈ 50 -year timespan covered, at

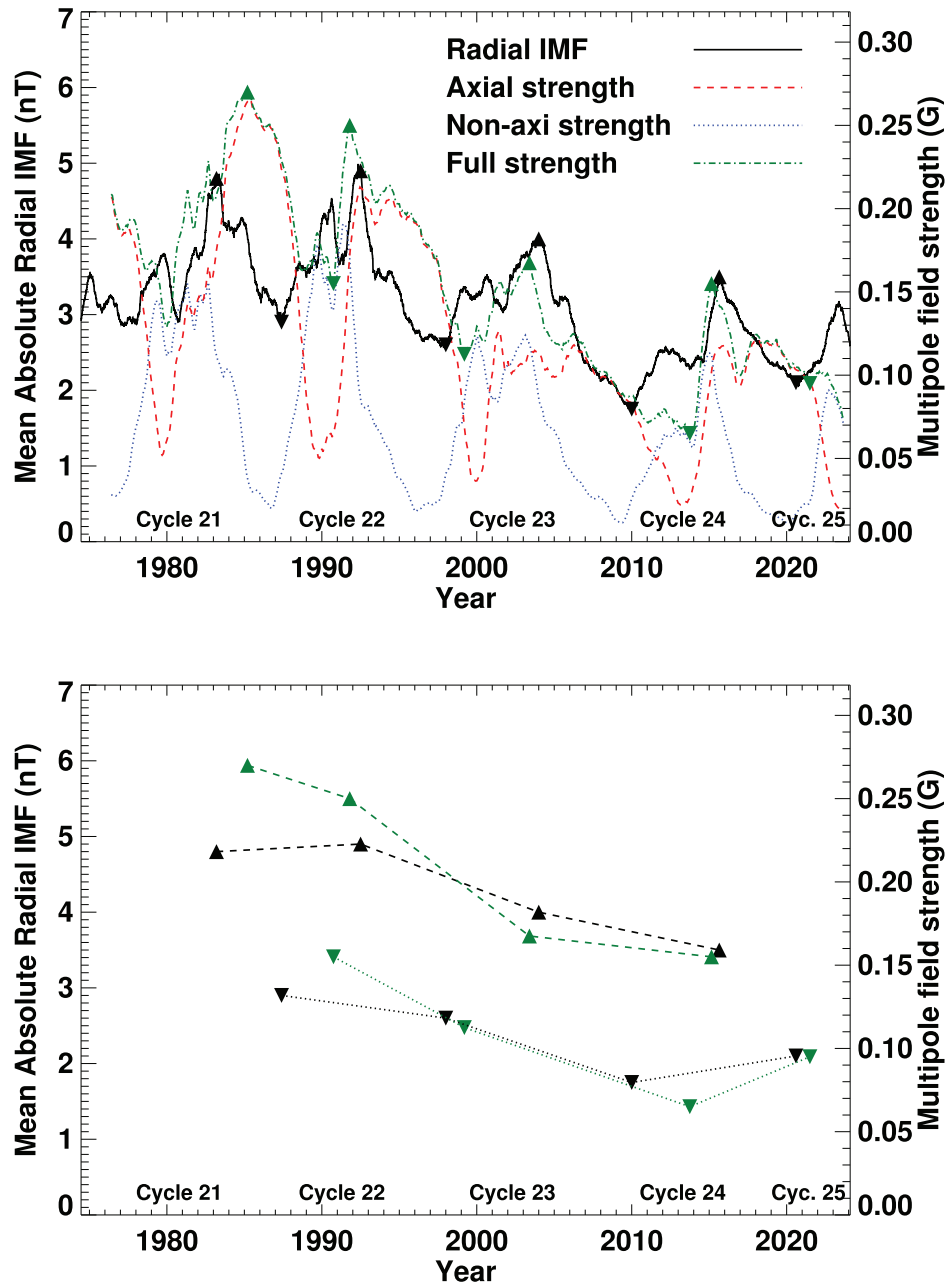


Figure 13. The mean absolute (unsigned) radial IMF from the OMNI database is plotted against time in the top panel, with 13-rotation smoothing (black solid line), with the following multipole strengths overplotted (right axis labels) for Wilcox data: the axial multipole strength (red dashed line), the non-axisymmetric multipole strength (blue dotted line), and the combined strength of all multipoles (green dot-dashed line). The cycle maximal and minimal values for the radial IMF and the combined multipole strength, discussed in the text, are represented by symbols to bring out the cycle-by-cycle behavior described in the text (stepwise decreases, anomalously low cycle 23 minimum values, In the bottom panel these cycle maximal and minimal values are plotted alone, connected by straight lines, to bring the cycle trends into sharper relief.) These plots emphasize that the relationship between the polar field strengths and the preceding cycle amplitudes is far from straightforward, and this is especially true for cycle 23.

least for cycles 21–24; as cycle 25 develops, it remains to be seen whether there will be an interruption or reversal of this trend. The radial IMF curve begins with two strong peaks, corresponding to the activity maxima of cycles 21 and 22, approximately equal in strength, and ends with two weak peaks, the cycle 23 and 24 activity maxima, with cycle 24 peaking more weakly than cycle 23. However, the decrease in radial IMF over

the past four cycles differs in character depending on whether one compares values during activity cycle maxima or minima: the activity minimum values took a more pronounced drop during cycle 23, from cycle 21 and 22 values of about 3 nT down to below 2 nT for cycle 23, and increased to 2 nT for cycle 24. The activity maximum values instead took strong cycle 21 and 22 values of about 5 nT, an intermediate cycle 23 value of about

4 nT, and a weak cycle 24 value of about 3.5 nT. If one compares ratios of cycle minimum/maximum radial IMF values then the cycle 23 ratio was clearly anomalously low. These details are worth noting because they relate to analogous patterns in the WSO data for the full coronal (combined multipoles) magnetic field strength.

Before discussing the combined WSO multipole strength, we first describe the non-axisymmetric and axisymmetric multipole curves in [Figure 13](#). Cycles 21–24 had double-peaked maxima in the non-axisymmetric WSO fields, with peaks of approximately equal strength during each of cycles 21–23, but curiously cycle 24's first peak reaching only about 0.6 G and its second much stronger at 0.11 G. This seems to be due to the slow, asymmetric rise phase of cycle 24 with only the northern hemisphere reaching some semblance of maximal activity. The taller cycle 24 second peak corresponds to the southern hemisphere finally and quickly coming to life – see [Section 4](#) and [Petrie \(2023\)](#). The radial IMF curve for cycle 24 also follows this basic structure around activity maximum. The WSO axisymmetric multipole curve shows a yet more pronounced stepwise decrease during cycle 23: after cycle 21 and 22 maximal values of about 0.26 and 0.21 G, the cycle 23 and 24 maxima were both around 0.12 G.

The curve for the combined strength of all WSO multipoles in [Figure 13](#) features cycle 21 and 22 maxima of about 0.27 and 0.25 G, followed by cycle 23 and 24 maxima of about 0.16 G, i.e. a stepwise decrease occurred at cycle 23. The combined curve minima, in contrast, took values 0.15, 0.11, 0.06, and 0.10 G, i.e. an anomalously low cycle 23 value stands out as with the OMNI IMF minima. Note that this combined WSO minimum value for cycle 23 did not occur until 2013/14, when cycle 24 was underway, challenging the definition of this cycle minimum. However, the cycle 23 combined minimum phase was unusually protracted for cycle 23 because of both the unusually weak polar fields of that cycle and also the slow, weak, asymmetric ascent of cycle 24 discussed further below; the cycle 23 combined curve takes values significantly below the cycle 24 minimum value for several years preceding 2014. The bottom panel of [Figure 13](#) shows only the cycle maximum and minimum values of the radial IMF and the full WSO multipole strength, represented by the same symbols as in the top panel, connected by straight lines to emphasize their cycle-to-cycle variation. Overall, we find a picture of a stepwise decrease in the radial IMF and the global solar field strength occurring during cycle 23, and an anomalously weak axial/polar field resulting from that cycle, accompanied by an anomalously weak radial IMF during cycle 23 activity minimum and a weakened radial IMF overall since cycle 23.

Comparing the axisymmetric and non-axisymmetric WSO curves in [Figure 13](#), the peaks in non-axisymmetric multipole strength generally coincide with axisymmetric curve gradients, consistent with the idea that the presence of ARs leads to polar field changes as in the Babcock-Leighton phenomenological model for the solar cycle. An important exception to this rule is the second non-axisymmetric peak of cycle 23 activity maximum, between the years 2001–2004. This non-axisymmetric peak is not accompanied by a significant changes in the axisymmetric multipole strength: instead of continuing its pre-2001 growing trend, the axisymmetric curve flattens, and only small and insignificant changes in axisymmetric strength occur

throughout the remainder of cycle 23, leaving the axisymmetric field much weaker at the end of cycle 23 than was the case at the end of each of the previous two cycles. Recalling that polar field change depends on both the magnetic flux of the ARs and their mean Joy's law tilt in the two hemispheres, the striking fact that this second peak in non-axisymmetric multipole strength during 2001–2004 is unaccompanied by significant change in the strength of the axisymmetric multipoles is consistent with the picture of the mean Joy's law tilt bias functionally vanishing in both hemispheres during this time, presented by [Petrie \(2012\)](#) and reviewed in [Section 2](#) in the discussion of [Figure 1](#): this weakening of the global solar field seems to have been due to Joy's law tilt bias (i.e., the latitudinal separation bias of the positive and negative AR centroids) in each hemisphere decreasing close to zero during this time, producing numerous weak, mixed-polarity, mutually-canceling poleward surges of decayed AR flux, producing no significant change in the polar fields. This fundamental change in the efficiency of the Babcock-Leighton mechanism explains both the anomalously weak cycle 23 polar fields and axisymmetric multipole strength, and the anomalously weak radial IMF during the decline and activity minimum of cycle 23. It remains to be seen whether these trends will be interrupted or reversed in cycle 25.

[Figure 13](#) also confirms that the major axial/polar field changes are confined to the maximum phase of the activity cycle, when the activity is strongest and located at relatively high latitudes, and not during the declining phase when the activity is closer to the equator, as shown in [Figure 1](#). This point was stressed by [Petrie \(2023\)](#) based on a detailed analysis of polar and hemispheric magnetic flux imbalances.

5.2 Hemispheric asymmetry and the radial interplanetary field during cycle 24

Accompanying the weaker global solar field since cycle 23 is the enhanced north-south hemispheric asymmetry of the AR flux emergence and the resulting global field. Here we demonstrate how this asymmetry influenced the radial IMF to an unusual degree during cycle 24. For KPVT/SOLIS, WSO and GONG data, [Figure 14](#) shows the radial IMF (B_r in heliographic coordinates, B_x in geocentric coordinates) with 3-CR (gray solid curves) and 13-CR (blue dotted curves) smoothing, with the signed axial even multipole strengths overplotted (red dashed curves). The resemblance between the even-order axial field curves and the radial IMF curve during the cycle 24 polar reversal is clear in each plot, and is much greater during this time than is generally the case for these quantities. This demonstrates the unusual, far-reaching influence of the even-order axial components in the global solar field during this time, due to the enhanced north-south hemispheric asymmetry. During the mid-2010s the even-order axial field was predominantly negative, and over the same period the radial IMF component measured in situ near Earth took a conspicuous and protracted dip into predominantly negative values. This behavior can be explained by the negative overall magnetic polarity bias of the polar fields during these times. During cycle 24 the stronger of the two poles, the south, reversed from positive to negative magnetic polarity, perturbing the even axial field to take negative values, such that magnetic flux from the negative south pole tended to dominate the IMF near Earth.

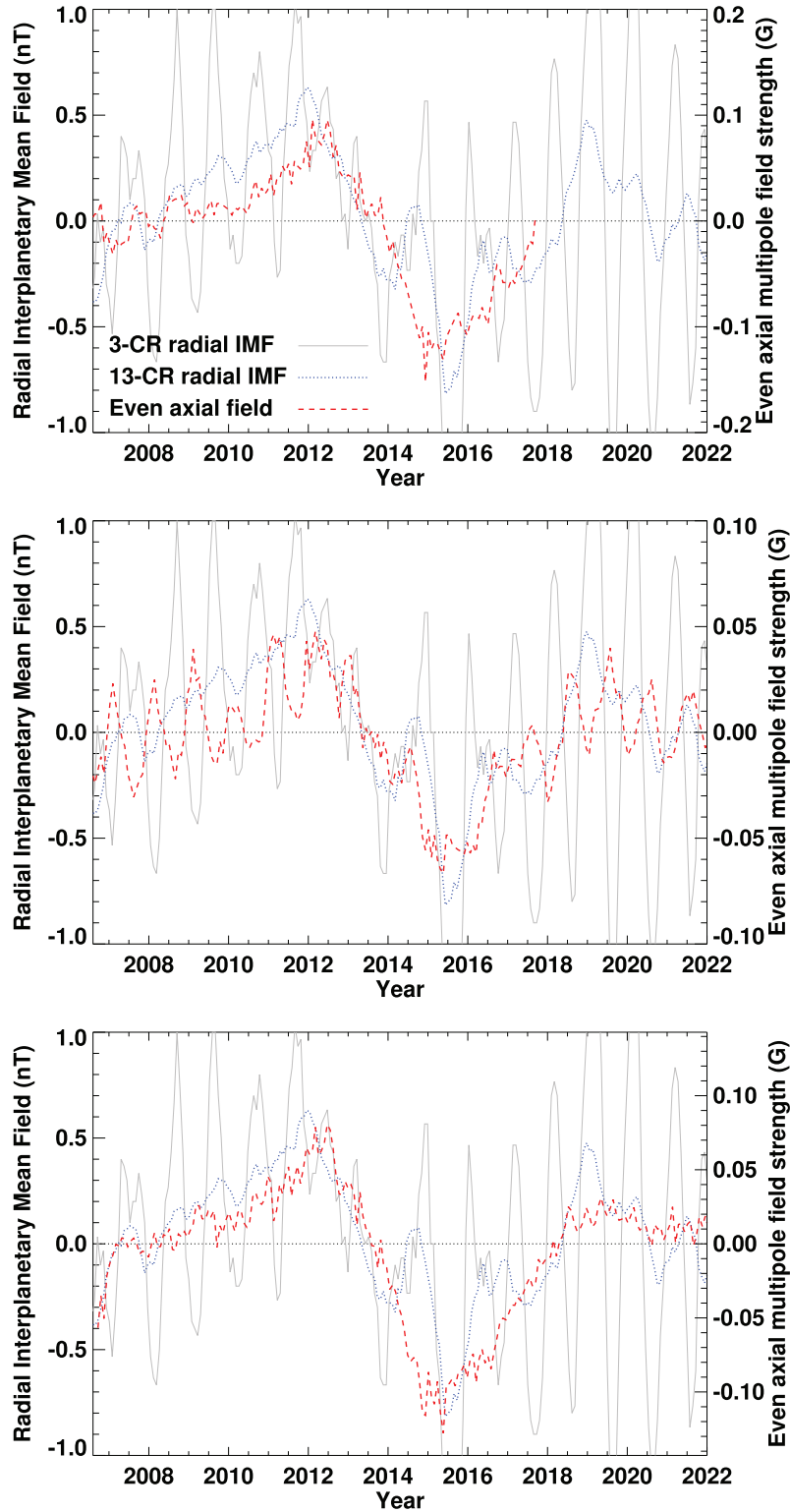


Figure 14. The radial IMF from the OMNI database is plotted against time over 2005–2022, with 3-CR (gray solid curves), and 13-CR (blue dotted curves) smoothing (blue dotted lines), with the signed axial even multipole strengths overplotted (red dashed lines, right axis labels), for KPVT and SOLIS (top), Wilcox (middle) and GONG (bottom) data. The resemblance between the axial quadrupole curves and the radial IMF curve during the cycle 24 polar reversal is clear in each plot, and is much greater than usual during this time.

A more detailed account of the sequence of events can be achieved by comparing Figure 14 to Figure 2: from having north and south polar fields of roughly equal strength and

opposite polarity in 2010, the negative north polar field decreased to near-zero values while the positive north maintained its strength. The even axial field responded to this overall

positive polar field bias by becoming positive shortly after 2010. Then, during 2013–2015, the south polar field swiftly and straightforwardly reversed polarity from positive to negative, passing quickly through zero, while the north polar field stayed weak throughout. The even axial field responded to this change in the overall polar bias from positive to negative by likewise reversing quickly and straightforwardly from positive to negative. The even axial field stayed negative while the north polar field finally became decisively positive in 2016, and only when the north polar field attained full strength a few years later did the even-order even axial field eventually lose its negative polarity bias. Figure 14 shows that the radial IMF followed all of the above changing trends of the even-order axial field.

The cycle 23 polar reversal was also asymmetric with the south polar field reversing much more slowly than the north. However, unlike the cycle 24 north polar field values, the cycle 23 south polar field values did not hover close to zero for a long time and so the cycle 23 polar field asymmetry was not as prominent. The odd-order axisymmetric multipole components were therefore not overpowered by the even-order ones during cycle 23 as they were during cycle 24. As Figure 12 shows, the only significant time period covered by the observations when the even-ordered axial multipoles were stronger than the odd-ordered ones was the several-year period around the cycle 24 polar reversal, and it is precisely during this time that Figure 14 shows the radial IMF following the axial even-ordered multipoles closely.

This correlation between the even-order axial field and the IMF around the time of the cycle 24 polar field reversal seems to be in tension with the comments at the end of Section 4 on the HCS displacement towards the weaker pole. An axial dipole and quadrupole of like/opposite signs implies a stronger north/south pole, which generally leads to a displacement of the HCS towards the north/south pole. The polarity of the weaker pole is expected to define the dominant polarity of the IMF because this polarity fills a larger solid angle in the heliosphere. Yet, during the cycle 24 polar field reversal it was the stronger pole that defined the polarity of the axial quadrupole moment and the even-order axial field, and also of the radial IMF. This is because the polar field asymmetry was so great during this time that there was no coronal hole to rival the one at the stronger pole.

6 Conclusions

Solar cycle 25 has begun in earnest, following the two strong, north-south symmetric cycles 21 and 22 and the two weak, more north-south asymmetric cycles 23 and 24. We investigated the recent evolution of the global photospheric and coronal magnetic field in comparison with the previous solar cycles well covered by full-disk synoptic magnetogram programs. Multiple synoptic magnetogram data sources were used: NSO's KPVT and SOLIS telescopes and GONG network, and Stanford University's WSO. Each synoptic magnetogram data source brought a different strength to the project: KPVT and SOLIS (1974–2017, cycles 21–24) and WSO (1976–present, cycles 21–25) provided long-term observations covering multiple solar cycles, WSO provided consistent observations with almost unchanged instrumentation from the mid-1970s

until the present day, KPVT and SOLIS provided spectropolarimetrically sensitive observations with 1'' plate scale, nominally 2'' spatial resolution, over four solar cycles, and GONG (2006–present) has covered nearly two decades continuously with observations of 2''.5 plate scale, 5'' spatial resolution.

Activity cycles 23 and 24 were not only significantly weaker than cycles 21 and 22, but also qualitatively more complex in structure. Cycles 21 and 22 featured faster, more decisive polar field reversals, evidently driven by a small number of large, strong poleward surges of decayed AR flux, with a more pronounced polarity bias dominated by the decayed flux of the trailing-sunspot polarity in each hemisphere. The structure of cycles 23 and 24 was complicated in particular by much greater hemispheric asymmetry, and the poleward flux surges were weaker, more numerous, and with less of a polarity bias, resulting in smaller, more gradual, and more hemispherically asymmetric polar field reversals. Whereas during cycles 21 and 22 the north and south polar field reversals occurred nearly simultaneously and took roughly the same length of time, during cycle 23/24 the south/north polar reversal took much longer than the north/south reversal. This global change in the solar field appears to have occurred during the second activity peak of cycle 23, coinciding with the disappearance of the mean Joy's law tilt bias in the two hemispheres.

PFSS model multipole analysis shows that a stepwise decrease in the global solar field strength occurred during cycle 23, and an anomalously weak axial/polar field resulted from that cycle. These solar changes were accompanied by an anomalously weak radial IMF during cycle 23 activity minimum and a weakened radial IMF overall since cycle 23. Signatures of Joy's law tilt bias disappearing and the polar field development stalling during cycle 23 were also evident in the multipoles: the non-axisymmetric multipole strength had a double-peaked activity maximum, and the second activity peak was unaccompanied by significant change in the axial multipole field strength. Such a significant level of activity with no significant axial field change was unique to cycle 23.

The coronal response to the recent hemispherically asymmetric photospheric field patterns is well captured by the axial quadrupole term of the standard PFSS coronal field model. It was shown that this large-scale axisymmetric component, dominated by the axial quadrupole, responded mostly to hemispheric asymmetries in polar field strength during the protracted polar field reversal of cycle 24. The axial quadrupole was a much more significant driver of global coronal structure around the time of this polar reversal than at any other time covered by the observations. In particular, for several years around the time of the cycle 24 polar field reversal the signed even-order axial field with its dominant axial quadrupole was unusually well correlated with the smoothed radial IMF measured in situ near Earth, indicating the strong relationship between the polar field bias and the radial IMF near Earth during those years. For most of the decade between 2010 and 2020 the signed even-ordered axial field, dominated by the axial quadrupole, represented the global influence of the polar field asymmetry on the structure of the corona and heliosphere during this time, to such a degree that its variations in strength and polarity bore an unusual resemblance to those of the radial IMF measured at 1 AU.

Cycle 25 has so far been more hemispherically symmetric than cycle 24, although the rising phase of cycle 25 began with

the southern leading the northern hemisphere. However, the north has recovered to lead this cycle's polar field reversal, more faintly echoing the swings of hemispheric dominance that characterized cycle 24. So far the cycle 25 field magnetic field structure has appeared comparable in amplitude to that of cycle 24, perhaps a little stronger, but with more hemispheric symmetry. The polar field reversal for cycle 25 has occurred, with no significant sign at the time of writing that further reversals or major north-south asymmetry will develop during this cycle.

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