Geomagnetic detection of the sectorial solar magnetic field and the historical peculiarity of minimum 23–24

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[1] Analysis is made of the geomagnetic-activity *aa* index covering solar cycle 11 to the beginning of 24, 1868–2011. Autocorrelation shows 27.0-d recurrent geomagnetic activity that is well-known to be prominent during solar-cycle minima; some minima also exhibit a smaller amount of 13.5-d recurrence. Previous work has shown that the recent solar minimum 23–24 exhibited 9.0 and 6.7-d recurrence in geomagnetic and heliospheric data, but those recurrence intervals were not prominently present during the preceding minima 21–22 and 22–23. Using annual-averages and solar-cycle averages of autocorrelations of the historical *aa* data, we put these observations into a long-term perspective: none of the 12 minima preceding 23–24 exhibited prominent 9.0 and 6.7-d geomagnetic activity recurrence. We show that the detection of these recurrence intervals can be traced to an unusual combination of sectorial spherical-harmonic structure in the solar magnetic field and anomalously low sunspot number. We speculate that 9.0 and 6.7-d recurrence is related to transient large-scale, low-latitude organization of the solar dynamo, such as seen in some numerical simulations. **Citation:** Love, J. J., E. Joshua Rigler, and S. E. Gibson (2012), Geomagnetic detection of the sectorial solar magnetic field and the historical peculiarity of minimum 23–24, *Geophys. Res. Lett.*, *39*, L04102, doi:10.1029/2011GL050702.

1. Introduction

[2] Recurrent geomagnetic activity changes over the course of each solar cycle. This can be understood in terms of the different phases of the Sun's dynamo cycle [e.g., *Solanki et al.*, 2006] and the oscillatory exchange of energy between the Sun's toroidal and poloidal magnetic field ingredients. At solar maximum, the Sun's magnetic field is primarily a toroidal quadrupole. Buoyancy brings toroidal field up to the solar surface, and with its emergence through the photosphere, sunspot groups are formed. During the declining phase of the solar cycle, energy shifts from the toroidal field to a poloidal dipolar field. This leads to a diminishment in sunspot number, an increase in broad regions of open coronal magnetic field lines and outflowing solar wind, corresponding to each end of the strengthening dipole, and the development of an organized heliospheric current sheet, corresponding to the dipolar magnetic equator. If the dipole is tilted with respect to the heliographic axis [e.g., *Suess*, 2008, Figure 7.1], then with 27.0-d synodic Carrington rotation of the Sun, the solar wind forms a heliospheric current sheet whose intersection with the heliographic equator is an Archimedean spiral [e.g., *Smith*, 2008]. This current sheet can potentially cross the Earth twice per solar rotation. Solar wind from the north and south heliospheric sectors drives low-level geomagnetic activity and small magnetic storms having 13.5-d lagged recurrence [e.g., *Mursula and Zieger*, 1998]. More often, however, the Sun is not quite so symmetrical. Either one dipolar end emits more solar wind than the other, or high-speed streams of solar wind are emitted from semi-isolated coronal holes that can persist for several months. As a result, the dominant interval for geomagnetic-activity recurrence is 27.0 d [e.g., *Tsurutani et al.*, 2006]. At sunspot minimum, the Sun's poloidal dipole field reaches its greatest strength and is roughly aligned with the Sun's rotational axis. During this time, recurrent geomagnetic activity is mild but detectable. For review of the toroidal-poloidal decomposition, see *Chandrasekhar* [1961, Appendix III].

[3] In contrast to this idealized description, the declining phase of cycle 23 and the depth of the ensuing minimum 23–24 were unusual [e.g., *Russell et al.*, 2010]. There were fewer sunspots in 2008 than in any year since 1913, minimum 14–15. Solar-wind data collected by the ACE satellite in 2005 record semi-persistent 9.0 and 6.7-d recurrence intervals [*Temmer et al.*, 2007], corresponding to the third and fourth harmonics of the synodic solar-rotational period. These same harmonics have been identified in geomagnetic activity and thermospheric density [*Lei et al.*, 2008; *Thayer et al.*, 2008], in auroral electrons [*Emery et al.*, 2009], and in relativistic radiation belt electrons [*Gibson et al.*, 2009], each for years near minimum 23–24. These observations have been interpreted in terms of low-latitude coronal holes [*de Toma*, 2012] and multipolar ingredients in the solar magnetic field [*Abramenko et al.*, 2010; *DeRosa et al.*, 2010] that gave structural complexity to the heliospheric current sheet [*McComas et al.*, 2006; *Hathaway and Suess*, 2008].

[4] Curiously, none of the above studies show prominent 9.0 and 6.7-d recurrence in data covering minima 21–22 and 22–23, leading to the perception that minimum 23–24 was unusual. This motivates our study. To establish whether or not minimum 23–24 was truly unusual in terms of recurrence, analysis of data covering many earlier solar cycles is required. Sunspots are not directly useful here, since they do not record recurrent phenomena. Fortunately, measures of geomagnetic activity, obtained from ground-based geomagnetic observatories [e.g., *Love*, 2008], are continuous in time from the middle of the 19th century to the present. Using autocorrelation methods, we analyze 13 solar-cycle minima of recurrent geomagnetic activity, 1868–2011, cycle 11 through to the beginning of 24. On the basis of comparisons between the historical geomagnetic results and other modern

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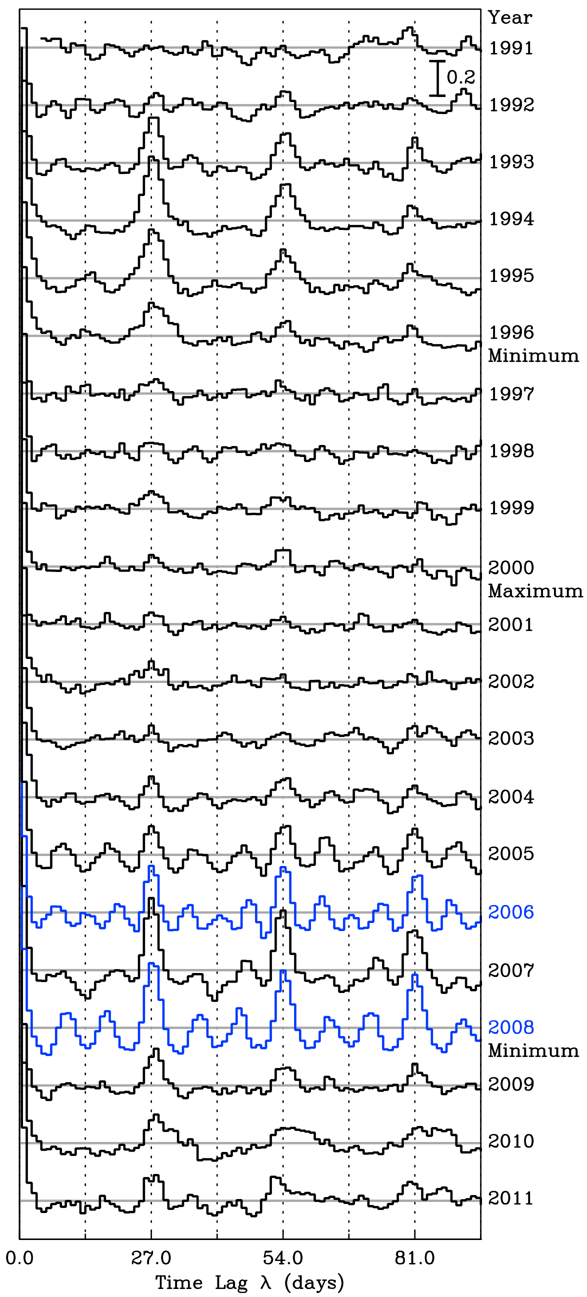

Figure 1. Annual averages of Pearson autocorrelation $r(\lambda)$ of the geomagnetic-activity *aa* index as a function of integer-day lag λ, 1991–2011. Results for 2006 and 2008 are shown in blue and should be compared with Figures 2 and 3. The amplitude scale is given in the upper right-hand corner, and the horizontal gray line for each autocorrelation shows its zero-level baseline.

data recording related solar-terrestrial phenomena for recent solar cycles, we can draw inferences about the long-term behavior of the solar magnetic field and better understand just how unusual minimum 23–24 actually was.

2. Data

[5] We analyze 5 different time series. (1) The three-hour geomagnetic-activity *aa* index, for years 1868–2011, from cycle 11 to the beginning of 24, is derived from a pair of ground-based observatories [*Mayaud*, 1980]. This index forms the basis of most of the analysis presented here. (2) Sunspot group numbers *G* [*Hoyt and Schatten*, 1998], 1976–2011, are a qualitative measure of variable solar activity. (3) Solar-wind velocity *V* and (4) the radial B_X component of the interplanetary magnetic field, for 2006 and 2008, were measured by the ACE [*Stone et al.*, 1999] satellite, 1.5 million km from the Earth and toward the Sun on the Sun-Earth line. (5) Wilcox Observatory potential-field models of the coronal magnetic field, 1976–2011, are fitted to magnetogram data with radial boundary conditions at the photosphere ($1.0R_\odot$) and in the corona ($2.5R_\odot$) [*Altschuler and Newkirk*, 1969; *Wang and Sheeley*, 1992]. These models consist of spherical-harmonic coefficients, but they can also be shown as synoptic maps.

3. Geomagnetic Autocorrelation 1991–2011

[6] To measure geomagnetic-activity recurrence, we calculate Pearson autocorrelations $r(\lambda)$ of the *aa* index as a function of integer-day lag λ. The computer algorithm [*Press et al.*, 1992, Chapter 14.5] is applied to 100.0-d over-lapping time-series segments of daily averages of *aa*, thus identifying recurrence that is persistent over a 100.0-d duration of time, or slightly more than three Carrington rotations. In Figure 1, we show annual averages of the autocorrelations for 1991–2011. During solar-cycle rise and maximum, such as 1998–2001, many magnetic storms result from the sporadic occurrence of coronal-mass ejections, and so there are few obvious features in the autocorrelation curves. But during solar-cycle decline and minimum, such as 1993–1996, cycles 22–23, 27.0-d recurrence is seen as distinctive peaks. Smaller peaks represent 13.5-drecurrence, for example, during 1995. There is a hint of a 6.7-d interval in 1992, but it does not persist for lags much greater than 27.0 d.

[7] Of more interest, here, are autocorrelations for the declining phase of cycle 23 and minimum 23–24. The year 2008 (blue) shows 9.0-d geomagnetic-activity recurrence intervals, corresponding to the third harmonic of synodic solar rotational, and for 2006 (blue), there is a 6.7-d recurrence interval, the fourth harmonic of solar rotation; these can be compared with the power spectra of *Thayer et al.* [2008, Figure 2]. It is fair to say that minimum 23–24 was different from 22–23. This assessment is consistent with that of *Emery et al.* [2009, Figure 5], who identified differences in the harmonic content of solar wind data between these two minima. Annual-average autocorrelation plots for years 1868–1993 are in the auxiliary material; a panoramic inspection of *aa* autocorrelation across many solar cycles is made in Section 6.[1]

4. Examples of 9.0-d and 6.7-d Recurrence

[8] In Figure 2 we plot 6 Carrington rotations of solar-terrestrial data for 2008 showing 9.0-d recurrence. The Wilcox synoptic maps of the radial coronal magnetic field at $2.5R_\odot$ show a warped "heliomagnetic equator", corresponding to the heliospheric current sheet that divides solar magnetic hemispheres of opposite polarities. For days 165–290, with

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050702.

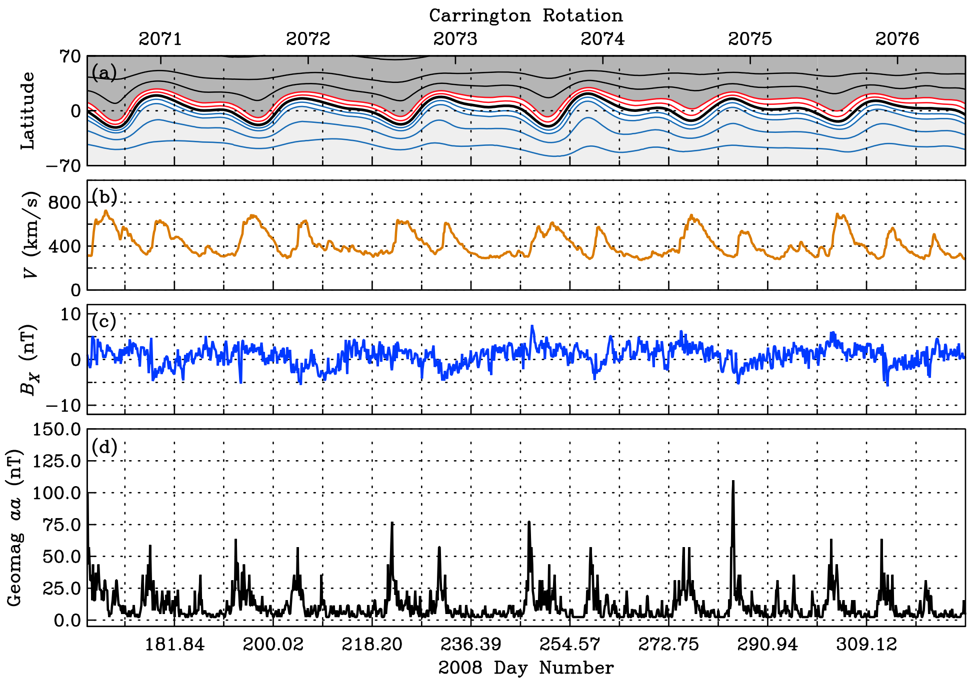

Figure 2. Stackplot of solar-terrestrial data and comparison with the geomagnetic-activity *aa* index for 2008, Carrington rotations 2071–2076. (a) Contour synoptic map of the radial coronal magnetic field between heliomagnetic latitudes of $\pm 70°$, at $2.5R_\odot$, as viewed from Earth, and on a continuous (left-to-right) time axis; contours of 0, 1, 2, 5, 10, 20 μT, with the magnetic equator shown as a heavy black line. (b) ACE solar wind velocity V and (c) radial component of the interplanetary magnetic field B_X. (d) 3-h values of the geomagnetic-activity *aa* index. To account for Sun-to-Earth propagation, the Carrington rotation maps are for day 162–325; for the interplanetary velocity, interplanetary magnetic field, and *aa* time series are shifted by 4 days, 166–329. Vertical lines denote 9.0-d increments.

each solar rotation, outward flowing solar wind on either side of the kink in the magnetic equator is measured by ACE as peaks in V separated by 9.0 d, followed by 18.0-d gaps of slower solar wind. The changing sign of ACE interplanetary magnetic field B_X indicates passage from one sector to another. After day 290, a slightly more regular, every-9.0-d pattern emerges. As for geomagnetic activity measured by *aa*, a corresponding 9.0 and 18.0-d recurrence results from solar wind-magnetospheric coupling.

[9] Similar data are shown in Figure 3. Here, the current sheet is especially scalloped, having a tidy 90°-sectorial structure. During this time, and especially for days 238–319, with each solar rotation, 6.7-d recurrence is seen in solar wind velocity V and geomagnetic activity *aa*; 13.5-d recurrence is seen in interplanetary magnetic field B_X. These observations, and those for Figure 2, are not of a heliosphere that is just generically non-axisymmetric, with a current sheet having random warps here and there. Instead, they show that the heliosphere can be organized in its asymmetry. Extending the inference made by *Mursula and Zieger* [1998], who focussed on the tilted dipole, the heliosphere near solar-cycle minimum is shaped by the Sun's low-degree spherical-harmonic poloidal field, and this can be detected in geomagnetic-activity recurrence intervals.

5. Sectorial Solar Magnetic Field

[10] We refer these observations to solar-cycle variation of the solar magnetic field. For each degree l and order m, we denote the Wilcox coronal magnetic field, radial at $2.5R_\odot$, as $\mathbf{B}_{lm}^{2.5}$. Spherical integration gives an energy spectrum,

$$E_{lm} = \frac{1}{4\pi}\oint_{4\pi} \mathbf{B}_{lm}^{2.5} \cdot \mathbf{B}_{lm}^{2.5} \sin\theta \, d\theta \, d\phi, \quad (1)$$

where θ is colatitude and ϕ is longitude. From this we estimate the relative proportion of energy per degree and order,

$$P_{lm} = \frac{E_{lm}}{\sum_{jk} E_{jk}}. \quad (2)$$

The spherical-harmonic ingredients contributing the greatest amount of nonaxisymmetry in the solar magnetic field are sectorial, for which $m = l$. For example, a sectorial quadrupolar field has four equatorial patches of open field (2 of each sign), and this can drive 6.7-d geomagnetic-activity recurrence. In Figure 4 we show time series of the proportion of dipolar P_{11} and quadrupolar P_{22} sectorial energy, 1976–2011; we also show, as a superposition, annual-average sunspot number G. Figure 4a is related to plots of dipole tilt seen in many papers, and it is equivalent to *Hoeksema* [2009], his Figure 2c divided by his Figure 2a. Otherwise, the sectorial quadrupole energy shown in Figure 4b is different from that shown in other work (contrast with *Abramenko et al.* [2010, Figure 5] and *DeRosa et al.* [2010, Figure 4]).

[11] In Figure 4, it is important to note that the correlation between both P_{11} and P_{22} with G is high from cycle minimum 20–21 (1976) until maximum 23 (2000). Afterwards

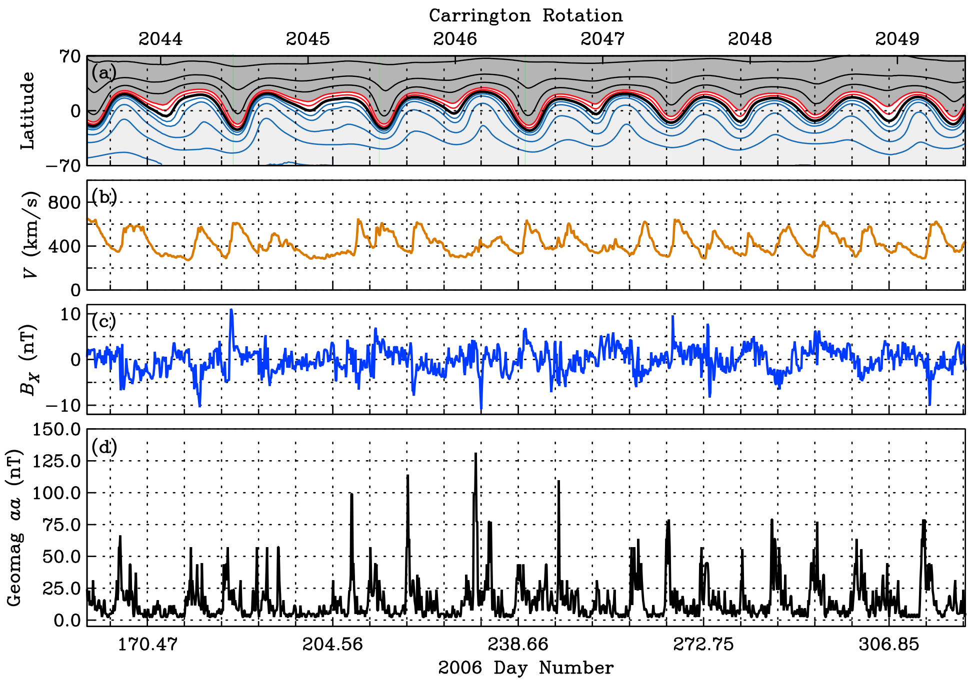

Figure 3. Similar to Figure 2, except for 2006, Carrington rotations 2044–2049. Vertical lines denote 6.7-d increments.

and into minimum 23–24 (2008), there is a departure, with sectorial energy remaining elevated during the declining phase of cycle 23, while sunspot numbers diminish and reach minimum. This combination is a phenomenological basis for recent 9.0 and 6.7-d *aa* recurrence: (1) non-axisymmetric, and especially sectorial, ingredients in the solar magnetic field give a non-axisymmetric heliosphere that drives geomagnetic recurrence, and (2) low sunspot numbers correspond to relatively few coronal-mass ejections and relatively little sporadic geomagnetic activity that would otherwise obscure measures of periodic recurrence.

6. Secular Change 1868–2011

[12] To put the preceding observations into a long-term context, in Figure 5 we show solar-cycle averages of geomagnetic *aa* autocorrelation $r(\lambda)$. Each average is taken over a duration extending from one sunspot maximum to the next, where, at each maximum, the axial dipole has a strength of approximately zero. Thus each average encloses a period of geomagnetic recurrence during solar-cycle decline and minimum. In the same figure, we also show the long-term average autocorrelation taken across all cycles (orange). Again, distinctive peaks correspond to 27.0-d recurrence, but we see, now, that the amplitude of recurrence has slowly changed from one cycle to another [*Sargent*, 1985]. In contradiction to *Rangarajan* [1991], 13.5-d recurrence is not always present. It is, however, seen for averages 15–16 and 16–17; anomalous autocorrelation, defined as the difference between an individual average and the long-term average, is shown for 16–17 (red). We have inspected the annual-average autocorrelations for each year since 1868 (auxiliary

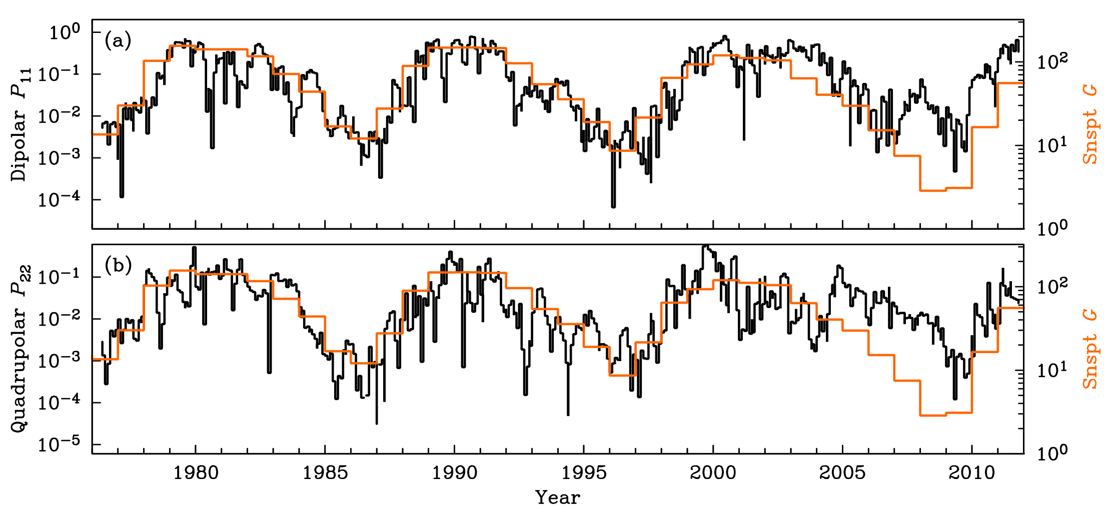

Figure 4. Proportion of (a) dipolar P_{11} and (b) quadrupolar P_{22} sectorial heliomagnetic energy, 1976–2011. Also shown in each case is sunspot number *G*.

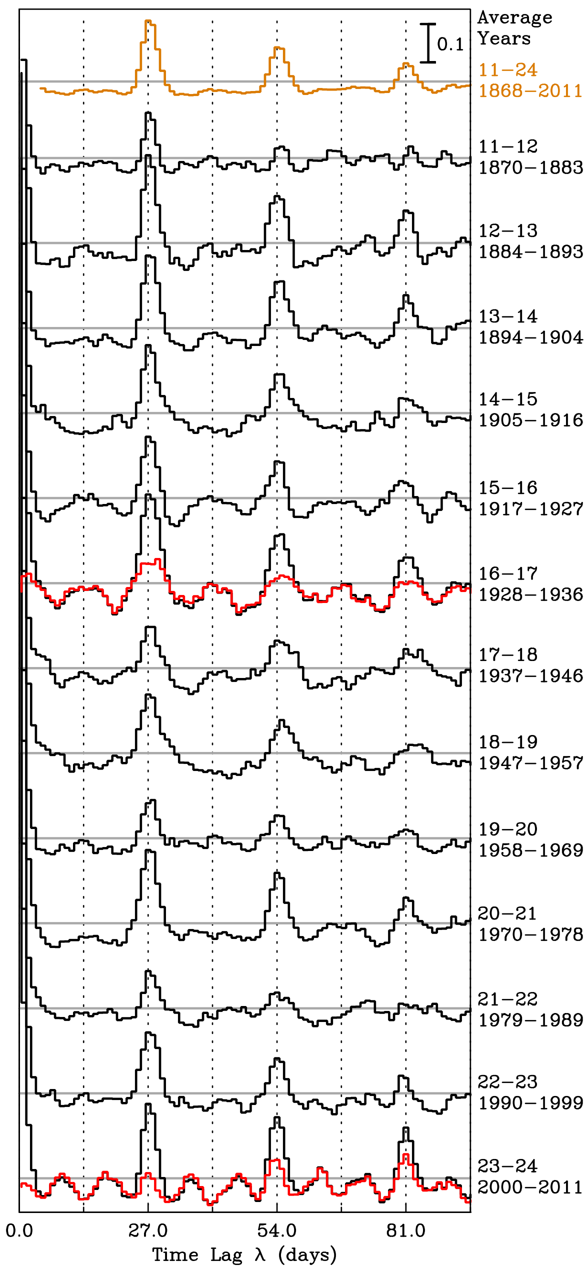

Figure 5. Solar cycle averages of $r(\lambda)$, cycles 11–24, 1868–2011. Also shown is the long-term average for all cycles (orange) and the anomalous autocorrelation (red) defined as the difference between each individual average and the long-term average. The amplitude scale is given in the upper right-hand corner, and the horizontal gray line for each autocorrelation shows its zero-level baseline.

material); 13.5-d recurrence is seen for some isolated years, such a 1895, 1922, and 1942, and, prominently, for the consecutive years of 1929 and 1930 [*Newton*, 1931]. Apparently, some solar polarity transitions are accomplished in a way that includes a tilting of the poloidal dipole, while other transitions result more from the diminishment of the axial dipole and its reappearance with the opposite polarity. With respect to historically quiet years, 1901 had an annual-average sunspot number of 2.5 and extremely low geomagnetic activity levels; *aa* autocorrelation shows a very faint 6.7-d recurrence for 1901, not nearly of the amplitude for 2006. Perhaps the 1901 solar magnetic field did not have very prominent sectorial ingredients.

7. Discussion and Dynamo Context

[13] With respect to the recent minimum 23–24 (2000–2011), Figure 5 and the material in the auxiliary material clearly show that it was unusual – even, "peculiar". None of the 12 preceding minima for cycles 11–23 show prominent 9.0 and 6.7-d *aa* recurrence. It is the nonaxisymmetric heliosphere that drives such recurrence, and since the heliosphere is controlled by the Sun, it is reasonable to conclude that the recent minimum 23–24 was distinguished by the solar dynamo obtaining a state of unusual asymmetry. Since solar convection is highly supercritical [e.g., *Miesch and Toomre*, 2009], a wide and continuous range of turbulent lengthscales, all shorter than the radius of the convection zone, is normal. But recent numerical simulations show that small-scale stellar convection cells can have larger-scale, low-latitude organization [*Dikpati and Gilman*, 2005; *Brown et al.*, 2008] that can be described in terms of low-degree, sectorial spherical harmonics. We speculate that the transient development of such large-scale nonaxisymmetric organization within the Sun leads to nonaxisymmetric structure in the solar poloidal field and in the heliosphere. This might be a physical explanation for sectorial structure in the solar magnetic field that can lead to 9.0 and 6.7-d geomagnetic-activity recurrence, such as seen during minimum 23–24.

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References

Abramenko, V., V. Yurchyshyn, J. Linker, Z. Mikić, J. Luhmann, and C. O. Lee (2010), Low-latitude coronal holes at the solar minimum of the 23 rd solar cycle, *Astrophys. J.*, *712*, 813–818.

Altschuler, M. D., and G. Newkirk Jr. (1969), Magnetic fields and the structure of the solar corona I: Methods of calculating coronal fields, *Sol. Phys.*, *9*, 131–149.

Brown, B. P., M. K. Browning, A. S. Brun, M. S. Miesch, and J. Toomre (2008), Rapidly rotating Suns and active nests of convection, *Astrophys. J.*, *689*, 1354–1372.

Chandrasekhar, S. (1961), *Hydrodynamic and Hydromagnetic Stability*, Clarendon, Oxford, U. K.

DeRosa, M. L., A. S. Brun, and J. T. Hoeksema (2010), Dipolar and quadrupolar magnetic field evolution over solar cycles 21, 22, and 23, in *Astrophysical Dynamics: From Stars to Galaxies, Proceedings of the International Astronomical Union*, edited by N. H. Brummell et al., *Symp. Int. Astron. Union*, *271*, 94–101.

de Toma, G. (2012), Evolution of coronal holes and implications for high-speed solar wind during the minimum between cycles 23 and 24, *Sol. Phys.*, doi:10.1007/s11207-0100-9677-2, in press.

Dikpati, M., and P. A. Gilman (2005), A shallow-water theory for the Sun's active longitudes, *Astrophys. J. Lett.*, *635*, L193–L196.

Emery, B. A., I. G. Richardson, D. S. Evans, and F. J. Rich (2009), Solar wind structure sources and periodicities of auroral electron power over three solar cycles, *J. Atmos. Sol. Terr. Phys.*, *71*, 1157–1175.

Gibson, S. E., J. U. Kozyra, G. de Toma, B. A. Emery, T. Onsager, and B. J. Thompson (2009), If the Sun is so quiet, why is the Earth ringing? A

comparison of two solar minimum intervals, *J. Geophys. Res.*, *114*, A09105, doi:10.1029/2009JA014342.
Hathaway, D. H., and S. T. Suess (2008), Solar cycle 23, in *The Heliosphere Through the Solar Activity Cycle*, edited by A. Balogh et al., pp. 21–39, Praxis, Chichester, U. K.
Hoeksema, J. T. (2009), Evolution of the large-scale magnetic field over three solar cycles, in *Solar and Stellar Variability: Impact on Earth and Planets, Proceedings of the International Astronomical Union*, edited by A. G. Kosovichev et al., *Symp. Int. Astron. Union*, *264*, 222–228.
Hoyt, D. V., and K. H. Schatten (1998), Group sunspot numbers: A new solar activity reconstruction, *Sol. Phys.*, *181*, 491–512.
Lei, J., J. P. Thayer, J. M. Forbes, E. K. Sutton, and R. S. Nerem (2008), Rotating solar coronal holes and periodic modulation of the upper atmosphere, *Geophys. Res. Lett.*, *35*, L10109, doi:10.1029/2008GL033875.
Love, J. J. (2008), Magnetic monitoring of Earth and space, *Phys. Today*, *61*, 31–37.
Mayaud, P. N. (1980), *Derivation, Meaning, and Use of Geomagnetic Indices*, *Geophys. Monogr. Ser.*, vol. 22, 154 pp., AGU, Washington, D. C.
McComas, D. J., H. A. Elliott, J. T. Gosling, and R. M. Skoug (2006), Ulysses observations of very different heliospheric structure during the declining phase of solar activity cycle 23, *Geophys. Res. Lett.*, *33*, L09102, doi:10.1029/2006GL025915.
Miesch, M. S., and J. Toomre (2009), Turbulence, magnetism, and shear in stellar interiors, *Annu. Rev. Fluid Mech.*, *41*, 317–345.
Mursula, K., and B. Zieger (1998), Solar excursion phases during the last 14 solar cycles, *Geophys. Res. Lett.*, *25*, 185–1851.
Newton, H. W. (1931), Magnetic storms and solar activity during 1930, *Observatory*, *54*, 163–165.
Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery (1992), *Numerical Recipes*, Cambridge Univ. Press, Cambridge, U. K.
Rangarajan, G. K. (1991), Variations in the strength of recurrent geomagnetic activity in solar cycles 11 to 21, *Proc. Indian Acad. Sci. Earth Planet. Sci.*, *100*, 49–54.
Russell, C. T., J. G. Luhmann, and L. K. Jian (2010), How unprecedented a solar minimum?, *Rev. Geophys.*, *48*, RG2004, doi:10.1029/2009RG000316.
Sargent, H. H., III (1985), Recurrent geomagnetic activity: Evidence for long-lived stability in solar wind structure, *J. Geophys. Res.*, *90*, 1425–1428.
Smith, E. J. (2008), The global heliospheric magnetic field, in *The Heliosphere Through the Solar Activity Cycle*, edited by A. Balogh et al., pp. 79–150, Praxis, Chichester, U. K.
Solanki, S. K., B. Inhester, and M. Schüssler (2006), The solar magnetic field, *Rep. Prog. Phys.*, *69*, 563–668.
Stone, E. C., A. M. Frandsen, R. A. Mewaldt, E. R. Christian, D. Margolies, J. F. Ormes, and F. Snow (1999), The Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 1–22.
Suess, S. T. (2008), Overview: The heliosphere then and now, in *The Heliosphere Through the Solar Activity Cycle*, edited by A. Balogh et al., pp. 251–280, Praxis, Chichester, U. K.
Temmer, M., B. Vršnak, and A. M. Veronig (2007), Periodic appearance of coronal holes and the related variation of solar wind parameters, *Sol. Phys.*, *241*, 371–383, doi:10.1007/s11207-007-0336-1.
Thayer, J. P., J. Lei, J. M. Forbes, E. K. Sutton, and R. S. Nerem (2008), Thermospheric density oscillations due to periodic solar wind high-speed streams, *J. Geophys. Res.*, *113*, A06307, doi:10.1029/2008JA013190.
Tsurutani, B., R. McPherron, W. Gonzalez, G. Lu, J. H. A. Sobral, and N. Gopalswamy (Eds.) (2006), *Recurrent Magnetic Storms: Corotating Solar Wind Streams*, *Geophys. Monogr. Ser.*, vol. 167, 340 pp., AGU, Washington, D. C.
Wang, Y.-M., and N. R. Sheeley Jr. (1992), On potential field models of the solar corona, *Astrophys. J.*, *392*, 310–319.

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