Solar Physics
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The Hale Solar Sector Boundary - Revisited

L. Svalgaard · P.H. Scherrer

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Keywords: Magnetic fields, Photosphere, Corona, Active Regions

1. The Hale Boundary Concept

Svalgaard and Wilcox (1976) introduced the concept of a Hale Solar Sector Boundary as that portion of a solar sector boundary (Svalgaard *et al.*, 1975) that is located in the solar hemisphere in which the change of magnetic polarity at the sector boundary is the same as the change of magnetic polarity from a preceding spot to a following spot (Figure 1).

They showed that above a Hale portion of a sector boundary, the green corona has maximum brightness, while above a non-Hale boundary, the green corona has minimum brightness. Using synoptic maps of the magnitude of the photospheric field strength observed at Mt. Wilson Observatory during 1967 to 1973 it was also found that the magnetic field is at a maximum at the Hale boundary, in concert with the green corona brightness. In this paper we extend to the present day (and confirm) that analysis using low-noise (5μT) magnetograms from the Wilcox Solar Observatory (WSO).

L. Svalgaard · P.H. Scherrer
HEPL, Via Ortega, Stanford Univ., Stanford, CA 94305 USA

L. Svalgaard
email: leif@leif.org

P.H. Scherrer
email: pscherrer@solar.stanford.edu

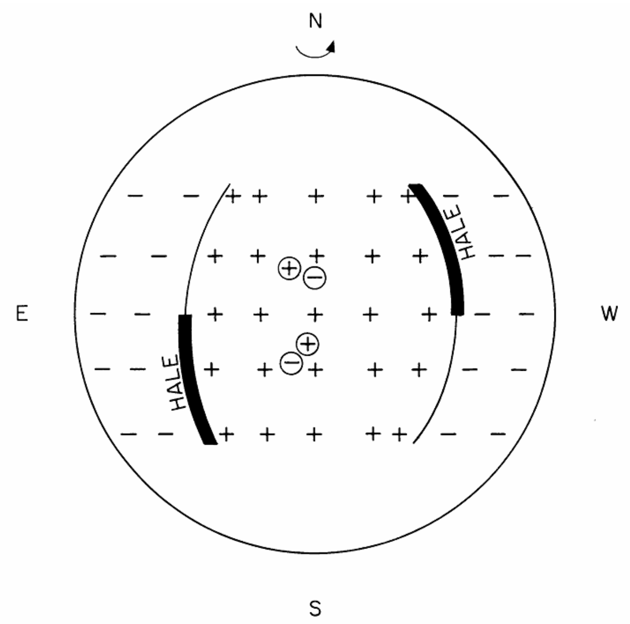

Figure 1. Schematic of the solar disk showing the portion of a sector boundary that is designated a Hale boundary, *i.e.* that portion of a sector boundary that is located in the solar hemisphere in which the change of magnetic polarity across the sector boundary is the same as the change of magnetic polarity from a preceding spot to a following spot. The spot polarities shown in the small circles correspond to even-numbered cycles, *e.g.* cycle 24. (Svalgaard and Wilcox, 1976).

2. Data Analysis

2.1. Solar Magnetograms

At WSO (http://wso.stanford.edu/) magnetograms using the 525 nm Fe I line are obtained every day with a sufficiently clear sky. Conditions permitting, several magnetograms may be secured on a given day. Observational details can be found elsewhere (Svalgaard *et al.*, 1978; Duvall *et al.*, 1978). The resulting magnetogram is a 21×21 array oriented north-south on the Sun and has not been remapped to any other coordinate system. In the analysis we ignore the annual variation of latitude of disk center, giving rise to less than 1% effect on the measured field (Duvall *et al.*, 1978). Magnetograms that were flagged with less-than-perfect conditions are not used; the remaining are used without any additional processing, filtering, cropping or other alterations of the original data. The magnetograms show the line-of-sight magnetic flux density over the aperture, not corrected for magnetograph saturation.

2.2. Sector Boundaries

Well-defined sector boundaries observed at Earth are taken from a compilation by Svalgaard (http://wso.stanford.edu/SB/SB.Svalgaard.html). When no spacecraft measurements were available, the sector polarity was inferred from its high-latitude geomagnetic signature (Svalgaard, 1973; Wilcox *et al.*, 1975). By convention, a well-defined sector boundary has four days of same polarity on either side of the boundary. Nominally, the sector boundary is assigned to the beginning of the UT day. Since WSO observes late in the UT day (noon is at 20:09 UT), the nominal transit time of $4\frac{1}{2}$ day must be taken to almost a day later to translate the time at Earth back to the time of central meridian passage of the sector boundary on the Sun. The Rosenberg-Coleman effect (Echer and Svalgaard, 2004) introduces a slight systematic extraneous, annual smearing of the sector boundary key times during the ascending phase of the solar cycle. We have not tried to correct for that, wishing to stay as close as possible to the raw data.

2.3. Superposed Epoch Procedure

For each well-defined sector boundary we check to see if there are magnetograms 5 days earlier. If so, all magnetograms on that day are selected. If no magnetograms were available, we try the day before or the day thereafter. If any magnetograms were selected they are stacked and an average magnetogram for all well-defined sector boundaries is computed. We perform the analysis separately for each type of polarity change boundary: (-,+) if the polarity when the sector boundary sweeps past the Earth changes from - (toward the Sun) to + (away from the Sun), and (+,-) for the opposite change.

With the typical variation of WSO field values and the number of sector boundaries, the statistical error of the averages is about 20μT or one contour line and color step. The zero-level of the WSO magnetograms is carefully controlled by observing the magnetic signal on a non-magnetic ($g = 0$) line before and after the magnetogram and subtracting the so determined, spurious systematic error (usually less that 10μT).

Since the Hale polarity changes between cycles, we perform the analysis separately for each cycle. Figure 2 shows the average field [strictly speaking: magnetogram] at boundaries that are Hale boundaries in the southern hemisphere and Figure 3 shows the situation for Hale boundaries in the northern hemisphere. Cycle 24 [not shown] does not yet have enough boundaries to allow a statistically significant result, although the same tendency as in cycle 22 is seen, as expected.

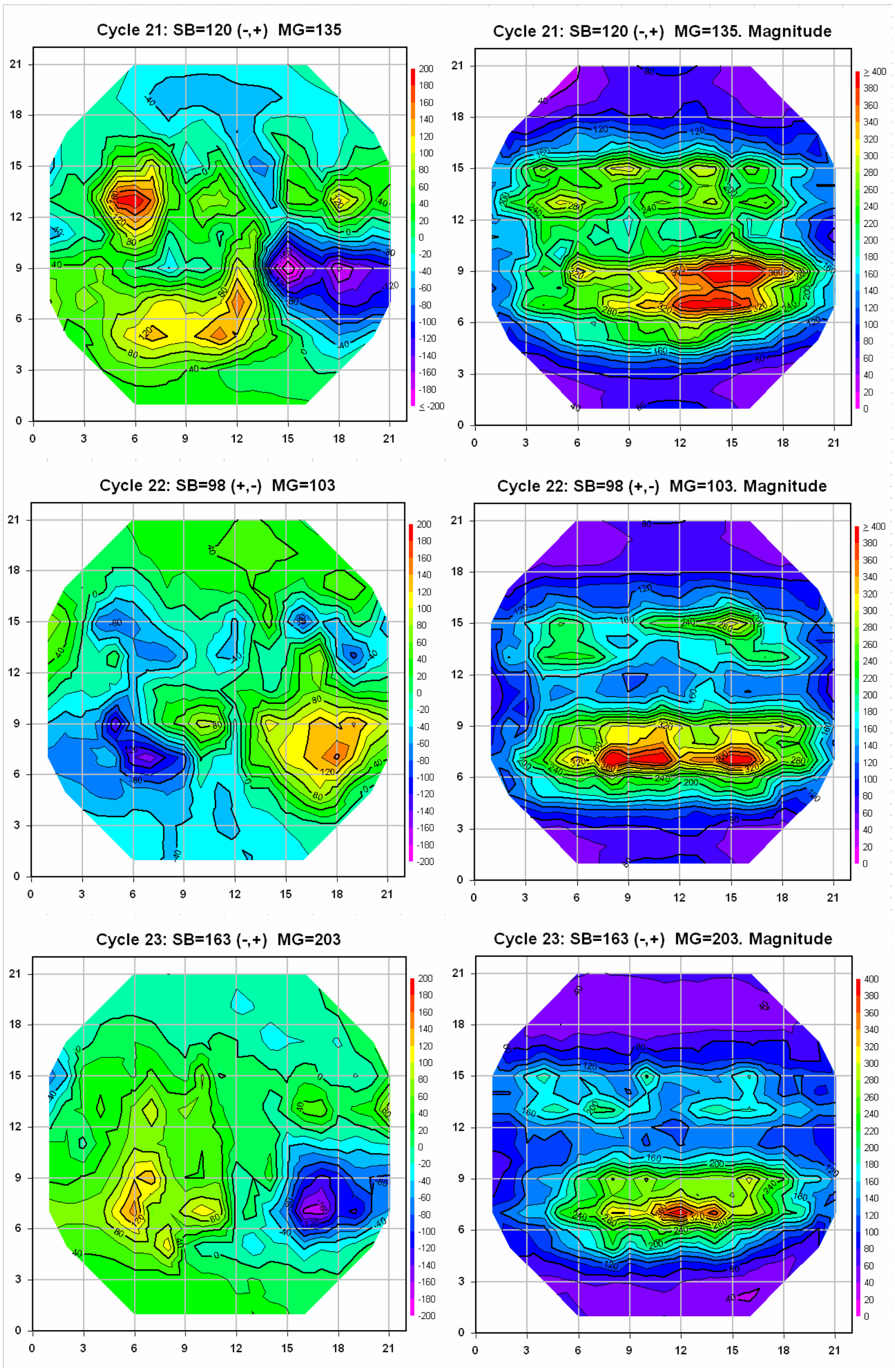

Figure 2. Superposed epoch analysis of the average photospheric line-of-sight magnetic field from WSO keyed on sector boundaries that are Hale boundaries in the southern hemisphere, for solar cycle 21 (-,+) boundaries, 22 (+,-), and 23 (-,+). The number of boundaries (SB) and magnetograms (MG) used are as indicated. The left-hand panel shows the average signed field, *e.g.* the sector structure in the photosphere. The right-hand panel shows the average magnitude of the field, confirming the original finding that the magnetic field is strongest at the Hale portion of sector boundaries. Flux densities are color coded in μT.

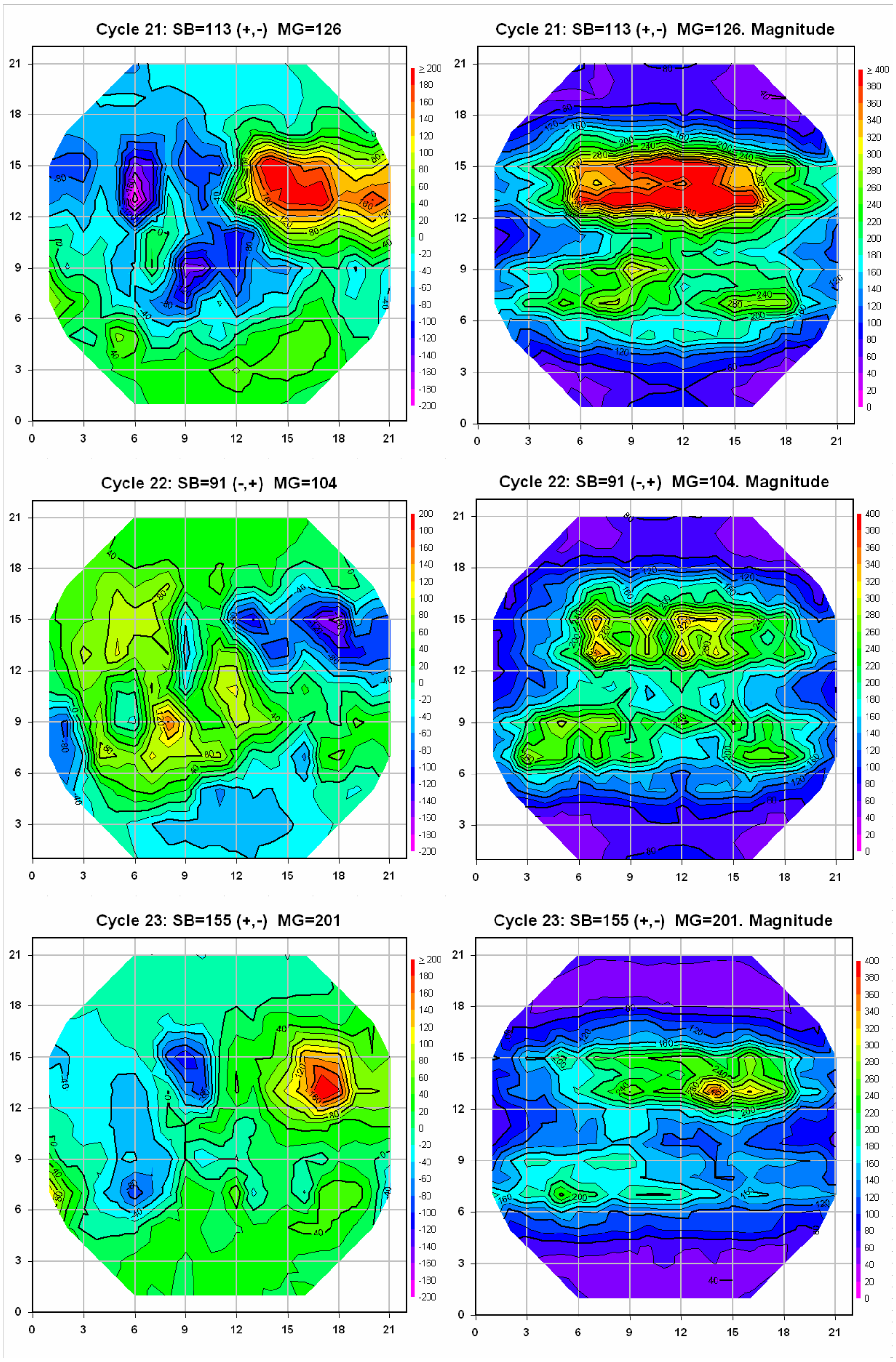

Figure 3. Superposed epoch analysis of the average photospheric line-of-sight magnetic field from WSO keyed on sector boundaries that are Hale boundaries in the northern hemisphere, for solar cycle 21 (+,-) boundaries, 22 (-,+), and 23 (+,-). The number of boundaries (SB) and magnetograms (MG) used are as indicated. The left-hand panel shows the average signed field, *e.g.* the sector structure in the photosphere. The right-hand panel shows the average magnitude of the field, confirming the original finding that the magnetic field is strongest at the Hale portion of sector boundaries. Flux densities are color coded in μT.

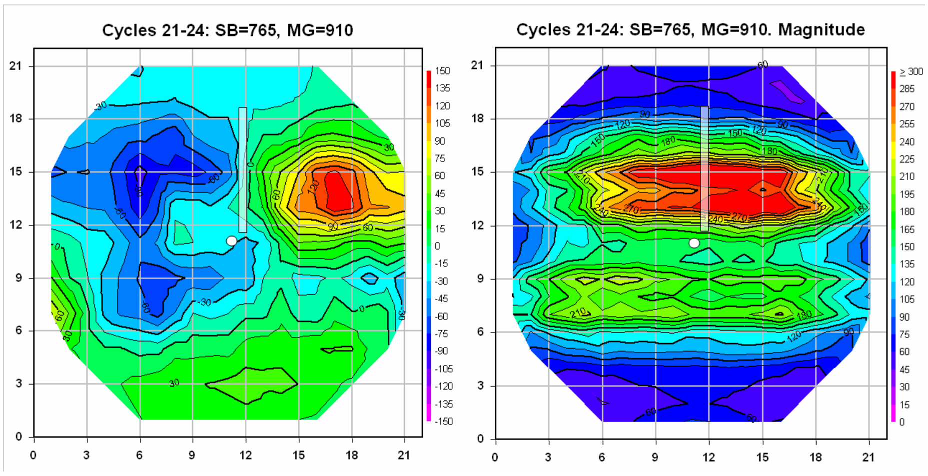

Figure 4. The average magnetogram for a nominal (+,-) Hale boundary in the northern hemisphere. 910 magnetograms superposed on 765 sector boundaries for the WSO observations 1976-2010. Some Data has been mirrored and sign-reversed as described in section 2.3. The sector boundary is marked by the semi-transparent bar.

To bring out the essential features of the patterns so clearly seen in Figures 2 and 3 we first mirror the data in Figure 2 about the equator. We then reverse the sign of the photospheric field for magnetograms superposed on (-,+) boundaries. Finally, we construct the average of all magnetograms data so treated. The result (Figure 4) shows (left) what the average sector boundary looks like in the photosphere and (right) the magnitude of the field, now for a nominal (+,-) Hale boundary.

3. Evolution with Phase of the Solar Cycle

The large-scale sector structure, observed in the corona and beyond, originates from extended magnetic fields on both sides of a Hale boundary in the photosphere (Figure 4) where the field strength is high. This means that the sources of a solar sector is largely limited to one hemisphere, namely where the polarity change matches that of the Hale polarity rule.

With the large amount of data from several cycles it is possible to study how the structures seen in the averaged magnetograms (Figure 4) vary with the phase of the cycle. We divide a cycle into the ascending phase (first third of the cycle), maximum (second third), and declining phase (last third) and compute the averages for each in the same way as for Figure 4. The result is shown in Figure 5. The same general behavior is seen regardless of phase with the expected variation of field strength over the cycle: Weaker during the ascending phase, strongest at maximum, and weakest during the declining phase. The equatorward progression of the sector with the progress of the cycle as well as Joy's law are clearly discernible. Note the reversal of polar field polarity.

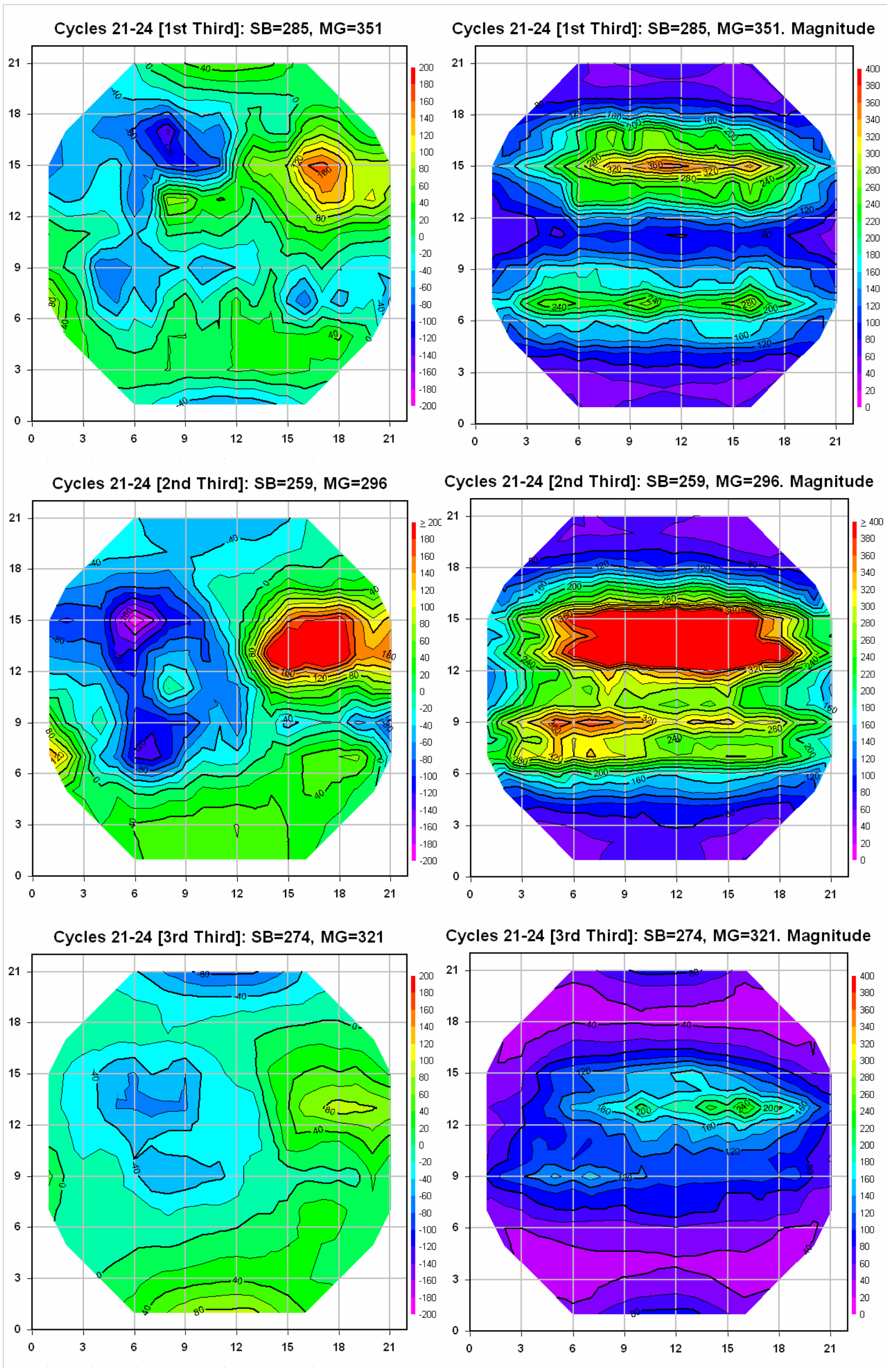

Figure 5. The average magnetogram for a nominal (+,-) Hale boundary in the northern hemisphere, for three different phases of the solar cycle, in the same format as for figure 4. The color scales are identical for all three phases.

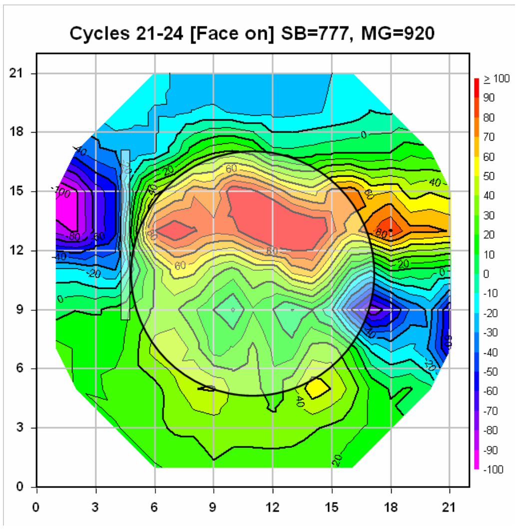

Figure 6: The average magnetogram for a nominal (+) sector seen 'face on' in the northern hemisphere. Appropriate data (WSO 1976-2010) has been mirrored and sign-reversed as described in section 2.3. The sector boundary is marked by the semi-transparent bar. The semi-transparent circle encloses the area that is mainly contributing to the Sun's mean field also measured at WSO (Scherrer *et al.*, 1977).

4. Discussion

The findings of preferential photospheric magnetic fields to heliospheric magnetic field (HMF) sector structures suggests one of a number of possibilities. The most obvious is that these photospheric structures are responsible for the HMF, and hence a correlation would simply be consistent with the Potential Field Source Surface models (Schatten *et al.*, 1969; Altschuler and Newkirk, 1969) wherein the HMF was seen as an extension of the solar field, as the solar wind plasma gripped the field and extended it into the solar wind. This, however, seems insufficient to explain our findings, since these models are symmetric, with regard to Left-Right or East-West handedness. So, if the cause were to be a coronal phenomenon, we would not expect the high degree of asymmetry we find.

From our understanding, of the relative high abundance of field orientation (active region formation, going along with Hale's polarity laws) relative to the Hale sector boundaries we show in Figure 1 and the orientation of the subsurface field in accordance with, say the Babcock-Leighton dynamo models, it seems that the association is more deeply rooted on the Sun, than in the corona. One such possible explanation has recently been put forward, and although it seems to be consistent with our findings, the author was aware of our earlier findings when his theory was developed, so this is not any new support for his theory.

This involves a recent shallow dynamo model (Schatten, 2009), which uses percolation and clustering to accumulate magnetic flux from ephemeral regions below the photosphere, where they gather together preferentially forming active regions near the low latitudes of high toroidal magnetic flux. To understand how this field gathering may relate to our observations, consider the following. Let us consider a dipole field forming near one of our Hale boundaries, say as oriented in the Northern hemisphere, as shown. Outward oriented field (ephemeral regions gathering into sunspots) could gather such field more readily, since the Western portion of the active region is embedded in an outward polarity background field.

Similarly the Eastern portion of active regions in these environs can gather field preferentially with these orientations (those orientations which are supported by Hale's laws). In other words, any little instability in this preferential ordering would grow from pre-existing field with the orientations from their inherent environment.

The geometry of the modern dynamo has a differing evolution than this shallow model: in conventional dynamo models, fields erupt from the Sun's interior outwards, whereas in the percolation model, field lines coalesce from small active regions where field lines are shed from the granulations' churning of Ephemeral regions. This temporal pattern is thus a difference between the standard dynamo theory and this new model.

Aside from these differences, however, the geometry of fields at any time, in the shallow model is similar to the Babcock-Leighton field geometry (both of course consistent with Hale's laws), hence either view of the Solar dynamo might equally fit our observations. So, perhaps it is too early to tell whether the observations are preferentially supporting which theory. So, although we are finding out some very important things about how field lines are evolving on and *in* the Sun, at present, it may be too early to distinguish whether the observations provide conclusive evidence on the exact location of the Sun's dynamo.

5. Conclusion

Acknowledgements The authors thank Ken Schatten for fruitful discussions.

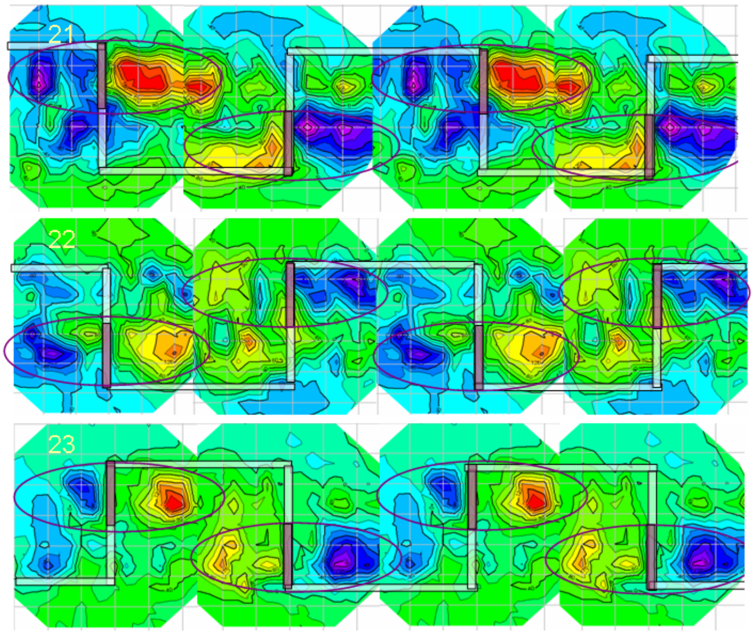

Figure 7. Schematic synoptic charts constructed by assuming a 4-sector structure and juxtaposing the central 90° of four average magnetograms for alternating sector boundaries [(+,-)(-,+)(+,-)(-,+)] for solar cycles 21 through 23. The large-scale neutral line is sketched using the semi-transparent bars. The Hale-portion is marked with the brown bars. Ovals outline the flux concentrations of the *signed* solar sectors.

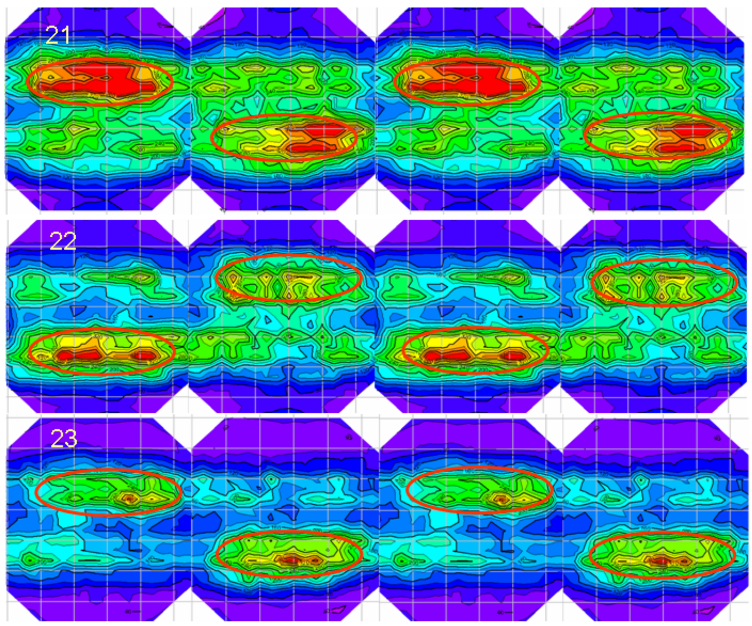

Figure 8. As Figure 7, except showing the *unsigned* magnetic field. The red ovals draw attention to and confirm the finding (Svalgaard *et al.*, 1975) that the field is at a maximum at the Hale-portion of sector boundaries.

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