The Hale Solar Sector Boundary - Revisited

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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. Figure 2 shows the observed relative brightness of the northern hemisphere green corona during sunspot cycles 18, 19, and 20 as a function of the distance from the solar sector boundary. The ordinate is the quantity 2(N − S)/(N + S), where N represents the brightness in the northern hemisphere of the green corona for each day, and S is the same for the southern hemisphere. Computing the relative brightness removes the effect of brightness variations through the sunspot cycle, and of variations in instrumental calibration.

Using synoptic maps of the magnitude of the photospheric field strength observed at Mt. Wilson Observatory during 1967 to 1973 it was also found...
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 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).
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 4½ 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; see also Figure 3. 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.

Figure 2. Superposed epoch analysis of the relative brightness in the northern hemisphere of the green coronal intensity in sunspot cycles 18, 19, and 20 near (+,-) sector boundaries and near (-,+)) boundaries. The vertical arrow indicates the time a sector boundary was observed at Earth, and the vertical dashed line indicates the location of the boundary on the Sun. The number, N, is the number of boundaries used. (Svalgaard and Wilcox, 1976).
Figure 3. The cross correlation coefficient between the sign of the solar mean field and the polarity of the heliospheric magnetic field at the Earth, showing a 5.5-day lag and the strong 27-day recurrence tendency. That the coefficient is not \( \approx -0.5 \) at lag \( +19 = 5.5 + 13.5 \) days shows that there, at times, is a significant 4-sector structure as well.

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 20 \( \mu \)T 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 10\( \mu \)T).

Since the Hale polarity changes between cycles, we perform the analysis separately for each cycle. Figure 4 shows the average field [strictly speaking: magnetogram] at boundaries that are Hale boundaries in the southern hemisphere and Figure 5 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.
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 5. 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 $\mu$T.
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 6) 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 6) 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 6. The result is shown in Figure 7. 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 7. 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 6. The color scales are identical for all three phases.
Figure 8. The average magnetogram for a nominal (+) sector seen ‘face on’ in the northern hemisphere. 920 magnetograms superposed on key times nine days before 777 sector boundaries (four days into the sector) for WSO observations 1976-2010. Appropriate data 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., 1972; Scherrer et al., 1977).

Figure 9. The yearly average of the magnetic field inside the semi-transparent circle (with radius 0.6 \( R_\odot \)) in Figure 8 (blue, circles) scaled to the magnitude of the WSO Mean Field (red, squares) compared with the heliospheric magnetic field at Earth (green, diamonds).

4. Solar Mean field

“Previous ground-based observations of the mean magnetic field, carried out at the Crimean and Stanford observatories, have shown that the polarity of the mean field is closely correlated with the polarity of the interplanetary magnetic field (after accounting for the 4 day transit time of the solar wind to earth), and it also displays a sector structure. This demonstrates that the interplanetary field is rooted in the large-scale pattern of the photospheric magnetic fields. However, the actual photospheric sources of the mean field have not been identified” (Stenflo, 1997).
We have moved one step closer to identifying the source of the mean field: it originates chiefly from a solar sector fed from alternating hemispheres, namely from the ones with the Hale boundary portion. It is noteworthy (Figure 9) that even as the solar mean magnetic field reaches values near zero at solar minimum, the yearly average of the heliospheric magnetic field does not drop below $\sim 4$ nT, consistent with a heliospheric magnetic field [HMF] ‘floor’ of that magnitude (Svalgaard and Cliver, 2007; Owens et al., 2008). The flux contribution of solar sectors (and whatever coronal holes they may harbor) when approaching minimum almost disappears. It is therefore remarkable that the HMF nevertheless shows a clear and recurrent sector structure, that matches the polarity of the solar mean field well.

Since the solar sectors originate in a hemisphere, we may understand the nature of the different rotation rates (e.g. 28.5 and 27 days (Svalgaard and Wilcox, 1975)) of the sector structure depending on the phase within the solar cycle (Hoeksema and Scherrer, 1987) as due to differential rotation of source regions at different latitudes.

5. Conclusion

Acknowledgements The authors thank ... (note the reduced point size)
**Figure 10.** 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 11.** As Figure 10, 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.
References


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