Asymmetric Solar Polar Field Reversals

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ABSTRACT

The solar polar fields reverse because magnetic flux from decaying sunspots moves towards the poles, with a preponderance of flux from the trailing spots. If there is a strong asymmetry in the sense that most activity is in the Northern Hemisphere, then that excess flux will move to the North Pole and reverse that pole first. If later on, there is a more activity in the South, then that flux will help reverse the South Pole. In this way, we get two humps in solar activity and a corresponding difference in time of reversals. Such difference was first noted in the very first observation of polar field reversal just after the maximum of the strongly asymmetric solar cycle 19, when the Southern Hemisphere was most active before sunspot maximum and the South Pole duly reversed first, followed by the Northern Hemisphere more than a year later, when that hemisphere became most active. Solar cycles since then have had the opposite asymmetry, with the Northern Hemisphere being most active early in the cycle. We show that polar field reversals for these cycles have as expected all happened first in the North. This is especially noteworthy for the present solar cycle 24. We suggest that the association of two or more peaks of solar activity when separated by hemispheres with correspondingly different times of polar field reversals is a general feature of the cycle, and that asymmetric polar field reversals are simply a consequence of asymmetry of solar activity.

Subject headings: Sun: surface magnetism — Sun: activity — Sun: dynamo

1. Introduction

In their epoch-making paper (Babcock & Babcock 1955) the Babcocks summarize their observations of weaker magnetic fields on the sun made possible by H. W. Babcock's invention of the solar magnetograph (Babcock 1953). Their findings have stood the test of time and include the following features: A *General Magnetic Field*, usually limited to heliographic latitudes greater than 55°, but with occasional extensions towards the equator. *Bipolar Magnetic Regions (BMRs)* in lower latitudes appearing as contiguous areas of opposite magnetic polarity obeying Hale's polarity laws, containing Ca II plages and, especially when the regions are young, occasionally sunspots. Filaments occur at the boundaries of regions or, alternatively, divide regions into parts of opposite polarity. As the regions age, they weaken and expand until lost in the background of irregular weak fields. And, occasionally, extended *Unipolar Magnetic Regions (UMRs)* of only one polarity, which can have a duration of many months as sources of recurrent geomagnetic storms. As noted, these observations provided objective evidence for the until then only inferential hypothesis that magnetic fields are fundamental to sunspots, plages, prominences, chromospheric structure, coronal and radio emissions, and ejection of neutral but ionized matter.

In 1959 H. D. Babcock reported (Babcock 1959) that the General Field had reversed polarity: "the south polar field reversed its sign between March and July, 1957. The sign of the north polar field, however, remained positive until November, 1958, when it rather abruptly became negative. For more than a year, the unexpected peculiarity was presented of two poles with the same sign". With the passing of time we find that the two poles having the same sign near their reversals is quite common and may have a simple explanation, already hinted at by the MWO observers "From the synoptic charts it is evident that there were many more UMRs in the north than in the south and, consequently, that appreciably less magnetic flux was moving to the south pole than to the north pole" (Bumba & Howard 1965). Waldmeier (1960) already noted, based on Babcock's observations that "if the northern and southern hemispheres are considered separately, the sunspot numbers reached a maximum in the south about one year earlier than in the north, and this suggests a physical connection with the earlier reversal of the south polar field".

2. Polar Field Reversal

In his celebrated 1961 paper H. W. Babcock (Babcock 1961) lists the reversal of the General Field as the first observation that must be explained by a theory of the solar cycle. Today we would rather use the narrower concept of Polar Fields rather than that of *a* General Field, as evidently the polar fields reverse at different times. Nevertheless, it is clear that the polar fields play a crucial role in the solar cycle, likely causative or at least symptomatic. In Babcock's phenomenological model "following parts of BMRs expand or migrate polewards so that their lines of force neutralize and then replace the initial dipolar field. The result, after sunspot maximum, is a main dipolar field of reversed polarity".

Let us assume that there is a strong asymmetry in the sense that all activity is in the Northern Hemisphere, then that excess trailing flux will move to the North Pole and reverse that pole, while nothing happens in the South. If later on, there is a lot of activity in the South, then that flux will help reverse the South Pole. In this way, we get two humps in solar activity, one in each hemisphere, and a corresponding difference in time of reversals. As noted above, such difference was first observed by Babcock (1959) from the very first observation of polar field reversal just after the maximum of the strongly asymmetric solar cycle 19. At that time, the Southern Hemisphere was most active before sunspot maximum and the South Pole duly reversed first, followed by the Northern Hemisphere more than a year later, when that hemisphere became most active. Solar cycles since then have had the opposite asymmetry, with the Northern Hemisphere being most active early in the cycle, Figures 1 and 2. Because cycles can have irregular maxima, e.g. cycle 21 (Feminella & Storini 1997), the integration performed in Figure 2 is helpful in discerning the larger-scale structure. The integration gives the necessary weight to the accumulated effect of many active regions. Polar field reversals for cycles 20 onward have as expected happened first in the North, as documented in the following section.

3. Observations

The net flux of the polar fields comes from a number of strong flux concentrations of vertical kilo-gauss elements with the overwhelmingly same polarity (Svalgaard et al. 1978; Shiota et al. 2012). Weaker elements and horizontal fields generally cancel out when averaged over the polar cap. During the course of a year, the solar rotation axis tips away from (N pole, March 7) and towards (N pole, September 9) the observer by 7.16 degrees. This, combined with a strong concentration of the flux near the pole and projection effects stemming from the line-of-sight field measurements, causes the observed polar fields to vary by a factor of up to two through the year (Svalgaard et al. 1978; Babcock & Babcock 1955). Because of the large aperture of the Wilcox Solar Observatory (WSO) magnetograph, the net magnetic flux over the aperture will be observed to be zero (the "apparent" reversal) well before the last of the old flux has disappeared as opposite polarity flux moving up from lower latitudes begins to fill the equatorward portions of the aperture. We are interested more in the "true" reversal when the last vestiges of the previous cycle's flux disappear and so shall use the higher-resolution magnetograms from Mount Wilson Observatory (MWO) to determine the time of polar field reversals. Even so, the MWO data do not represent the very near polar fields well and thus still yield reversal times a little ahead of the final disappearence of the flux at the pole, but at least consistently.

The MWO supersynoptic maps (Ulrich et al. 2002), show, Figure 3, how the trailing polarity moves polewards, canceling out the old polarity as it goes. For the four recent cycles depicted, the North pole clearly reverses first in every cycle, as shown by little circles at the reversals . The difference in time of reversal is typically of the order of a year. The vertical 'stripes' show, Figure 4, another characteristic of the reversal: that poleward migration has a strong longitudinal component (in a coordinate system rotating with the plasma), taking place in the same longitude interval over extended periods of time, rather than on a broad 'front' advancing in latitude. Furthermore, most of the leading polarity also migrates towards the pole, cancelling part of the trailing polarity as it goes. The net result is polar magnetic flux that is just a tiny fraction of the flux emerged in the sunspots.

In Cycle 20, peaking about 1969, the pre-maximum activity was strongly concentrated in the North, so the North polar field should reverse first. Unfortunately, the polar fields were weak and could not be clearly observed above the magnetograph noise making it difficult to determine the precise timing of the reversals (Howard 1972). It is well-known that prominences, filaments, and microwave and green corona emissions can give further information about the polar field extent, in particular, the 'Rush to the Poles' (RTP) phenomenon (Altrock 2003; Gopalswamy et al. 2003) that signals the cessation of high-latitude activity is a marker for the time of polarity reversal. Figure 5 shows that the RTP for cycle 20 happened in the North well before the South, although matters are complicated by the presence of a secondary prominence zone (Waldmeier 1973).

The asymmetry is particularly clear for the current cycle 24, where the North polar flux and the northern pole coronal hole have already practically disappeared, while the South polar flux has only decreased slightly, as has been noted by several authors, e.g. Hoeksema (2012), Shiota et al. (2012), Altrock (2012), and Gopalswamy et al. (2012). We might expect the South polar fields to reverse, perhaps abruptly as the North in cycle 19, as activity eventually picks up in the Southern Hemisphere (as it already has at the time of writing). Measuring the extent of the polar coronal holes using the relationship between coronal holes and polar flux is a valuable tool that avoids the projection effects suffered by magnetograms (Kirk et al. 2009; Webber et al. 2012). Figure 6 shows the recent evolution of the polar coronal hole area, determined both by locating the hole boundary at the limb (left panel) and by observing the holes on the disk (right panel), consistent with the observations of the magnetic field, as the areas of the polar coronal holes are proxies for the magnetic flux in the polar regions, e.g. Wang (2009). In particular, the disappearance of a hole marks effectively the polar field reversal (clearly seen for the North in Cycle 24).

4. Discussion

It seems from the asymmetry in solar activity (measured e.g. by sunspots) that the two hemispheres are only weakly coupled (Norton & Gallagher 2010) and develop rather independently, especially when it comes to corresponding polar field reversals, a relationship which may have been implicit in earlier work (e. g. Durrant & Wilson (2003)), but that we here make explicit. One can look at the solar cycle as a continuous conversion of poloidal field to toroidal field and back to poloidal field. While the generation of toroidal field is probably a rather deterministic and orderly process, the generation of poloidal field seems to be a much more random process, as only a very small fraction (1 to 2%) of the toroidal field is converted to polar fields by diffusion and/or circulation. E.g. Choudhuri et al. (2007) argue that the Babcock—Leighton mechanism, in which the poloidal field is produced from the decay of tilted bipolar sunspots, involves randomness because the convective buffeting on rising flux tubes causes a scatter in the tilt angles. From the evidence presented here it would appear that the standard Babcock-Leighton paradigm is sufficient to explain the connection between hemispherically asymmetric solar activity and the observed differences in times of polar field reversals in corresponding hemispheres. In every cycle since the polar fields were first observed, the reversals have been at different times, and simply related to the prevailing activity asymmetry readily produced by a dynamo, e.g. as suggested by Parker (1971). In case of a 'complicated' cycle with multiple surges of activity, the polar field reversals will then also show complicated behavior, perhaps with multiple reversals. We do not here address the wider issue of how solar activity can be asymmetric, including possible 'memory' effects suggested by the persistence of the asymmetry over several consecutive cycles (e.g. Zolotova et al. (2010); Muraközy & Ludmány (2012)), but simply take the asymmetry of each cycle as a given property of that cycle.

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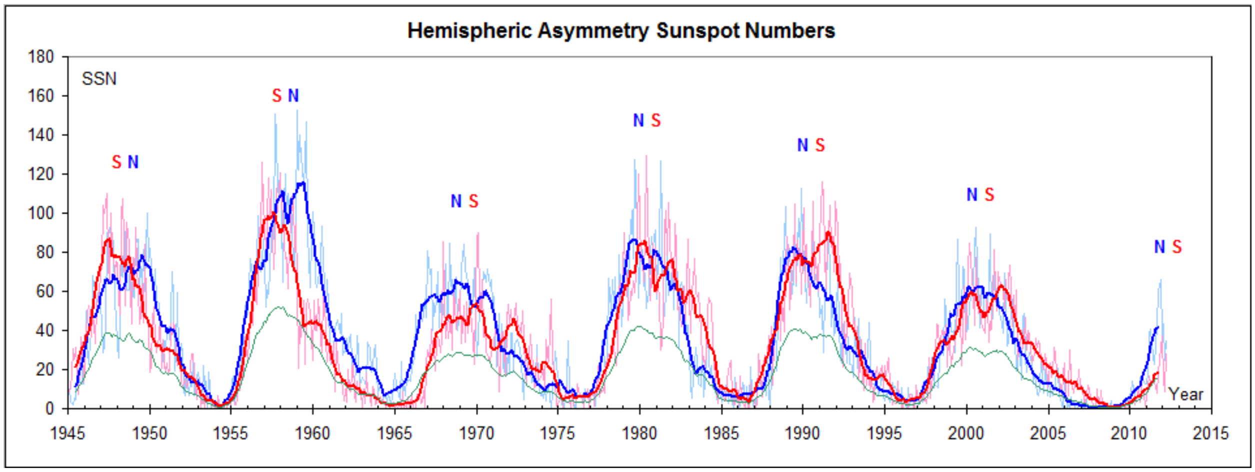

Fig. 1.— Sunspot Numbers since 1945 separated by hemisphere (blue - north; red - south). The thin curves show monthly means while the thick curves show the smoothed means. Each cycle is annotated with an estimate of which hemispheres were the most active before and after solar maximum. For reference, the thin (green) line at the bottom shows the full-disk smoothed average, scaled down by a factor of four. Data before 1992 are from Temmer et al. (2006) and thereafter from SIDC (http://www.sidc.be/sunspot-data/dailyssn.php).

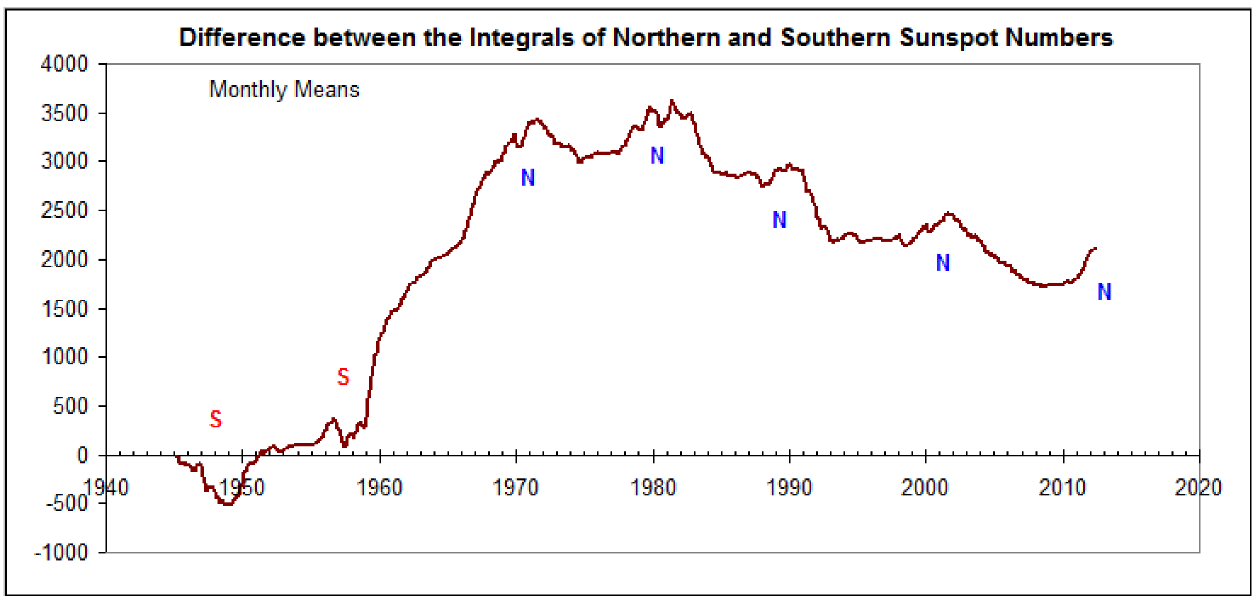

Fig. 2.— The Difference between the integrals (since 1945) of monthly sunspot numbers separately for the Northern and Southern hemispheres. A dip at solar maximum means that the Southern hemisphere produced more sunspots leading up to solar maximum. A peak at solar maximum means that the Northern hemisphere was more active leading up to the maximum.

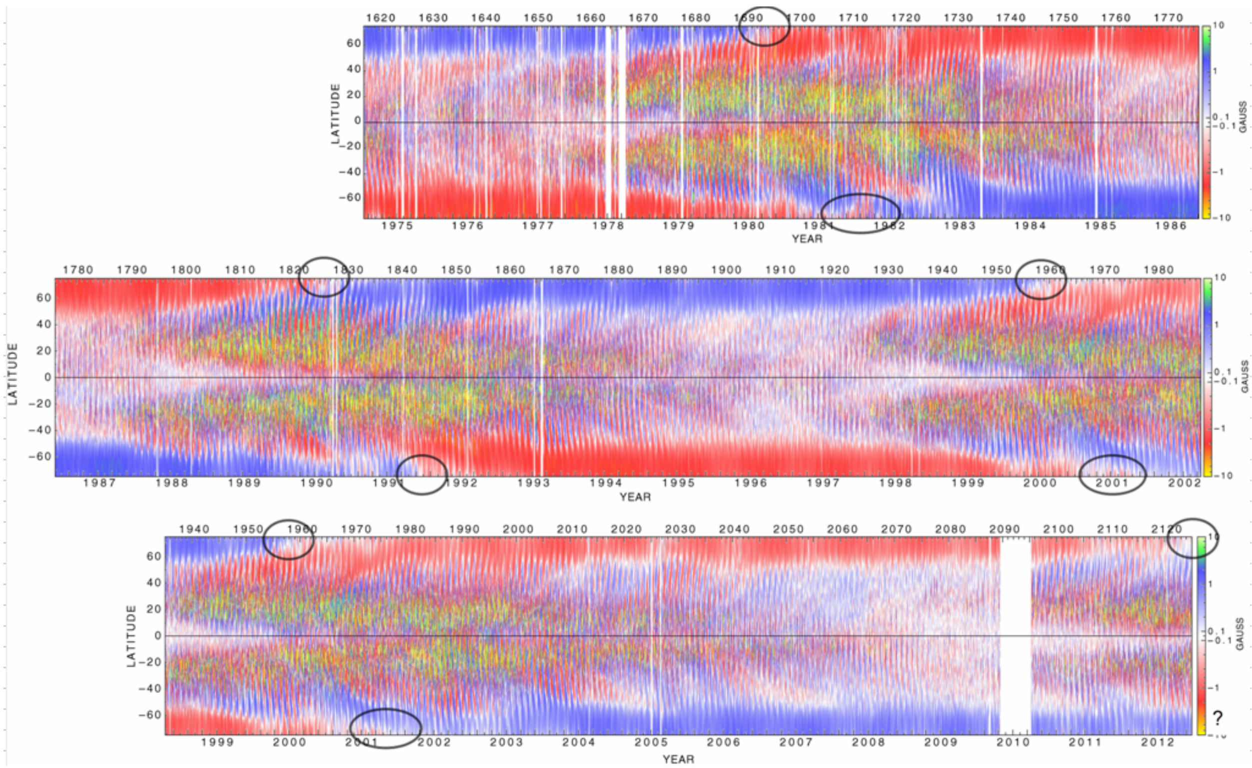

Fig. 3.— MWO Supersynoptic maps of the polar reversals at the solar maxima in 1980, 1990, 2001, and (upcoming after) 2012. A supersynoptic map consists of a large number of time-compressed and time-reversed ordinary synoptic maps stacked sideways in time (Years at the bottom of each panel and Carrington Rotations at the top). Positive (away from the surface) polarity is in blue (and green), while negative polarity (towards the surface) is in red (and yellow). Courtesy Roger Ulrich/MWO (Ulrich et al. 2002) (http://obs.astro.ucla.edu/intro.html). Small ovals highlight the reversals.

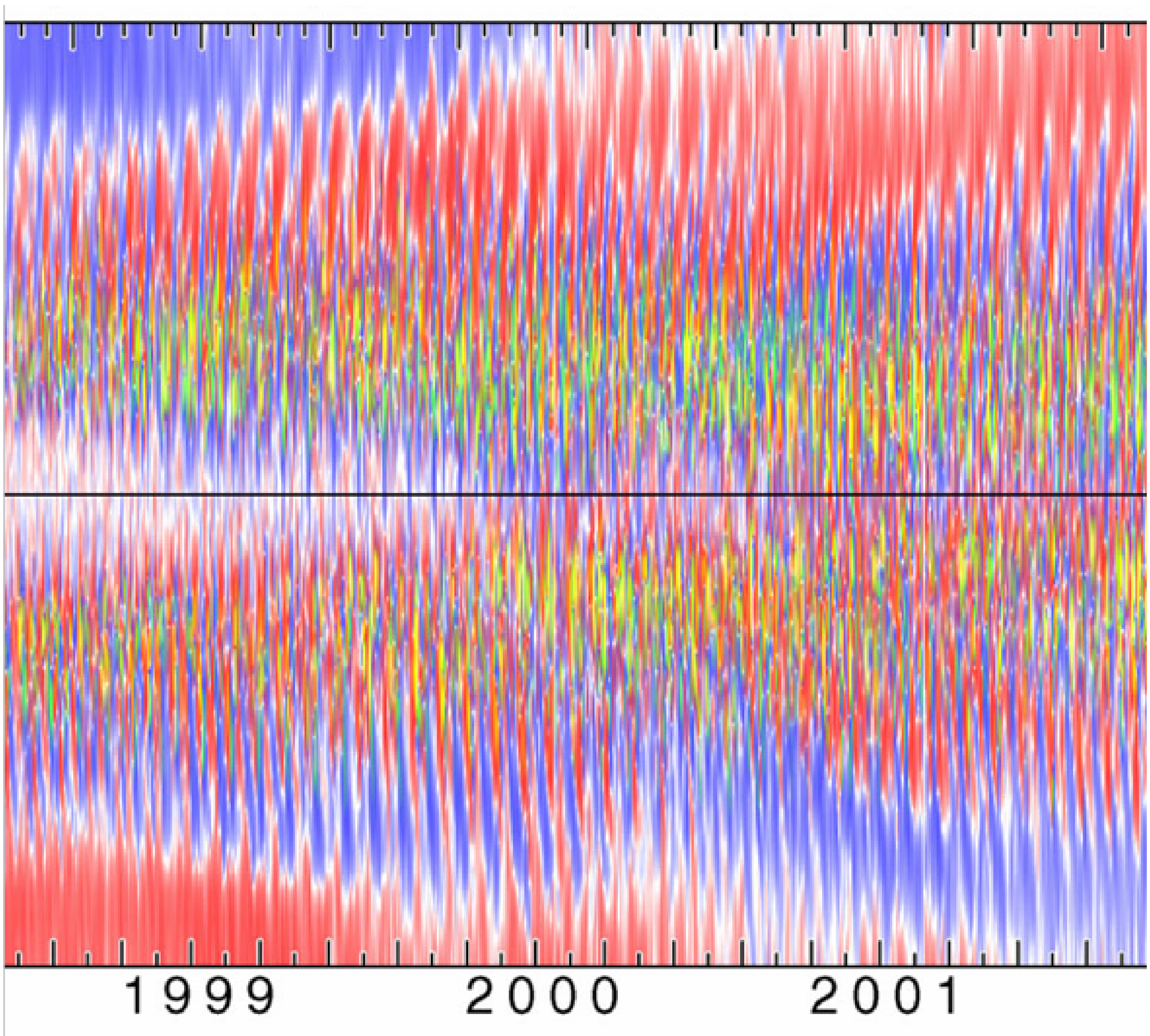

Fig. 4.— A blow-up of a part of Figure 3 showing the migration of flux of both polarities as narrow streams in longitude.

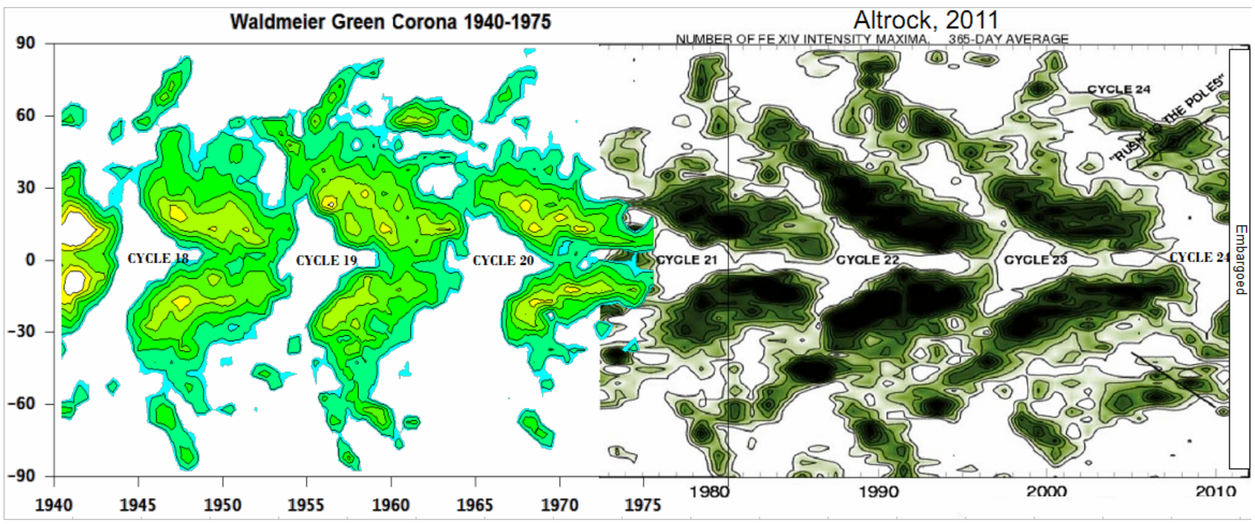

Fig. 5.— Contour maps of the distribution in latitude of Green Corona maxima derived (left) from observations by Waldmeier (1978) and (right) from observations by Altrock (2011). The maps show the probability of finding local maxima of the Green Corona as a function of latitude and time. The 'Rush to the Poles' (Altrock 2003) delineates in parallel the poleward migration of the polar cap boundary, an indicator of the reversal process.

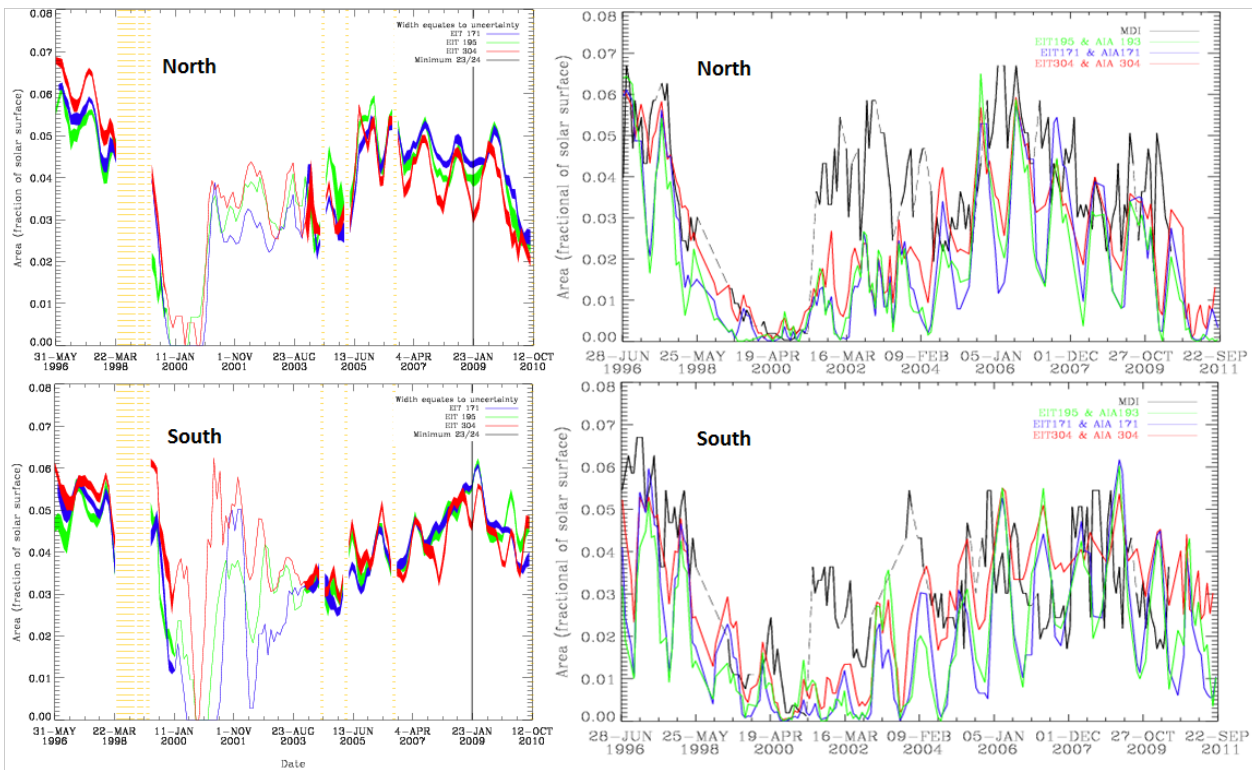

Fig. 6.— Northern and Southern polar coronal hole fraction versus time derived from EIT, AIA, and MDI data (Kirk et al. 2009; Webber et al. 2012). The areas were determined both by locating the hole boundary at the limb (left panel) and by observing the holes on the disk (right panel).